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NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

BP 25, 7 RUE ANCELLE, F-92201 NEUILLY-SUR-SEINE CEDEX, FRANCE

RTO MEETING PROCEEDINGS 76

Blowing Hot and Cold: Protecting Against Climatic Extremes

(Souffler le chaud et le froid: comment se protéger contre les conditions climatiques extrêmes)

Papers presented at the RTO Human Factors and Medicine Panel (HFM) Symposium held in Dresden, Germany, 8-10 October 2001.

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The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote cooperative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective coordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also coordinates RTO's cooperation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of initial cooperation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS Studies, Analysis and Simulation Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier cooperation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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Blowing Hot and Cold: Protecting Against Climatic Extremes

(RTO MP-076 / HFM-061)

Executive Summary

On 8-10 October 2001, NATO and Partner for Peace nationals met in Dresden, Germany, to discuss the interaction between the climate, the clothing and equipment, and the physiology of the soldier in relation to its impact on the soldier's, health and operational performance. 118 people participated in the meeting, originating from 20 countries, attending a total of 43 papers. Session topics were: 'Advances in clothing technology', 'advanced technology for heat stress mitigation', 'military benefits of physiological adaptation to heat and cold', and 'modelling, monitoring and thermal limits'.

An underlying theme of the conference was the implication the research presented has for the fight against terrorism. The optimisation of the protection of emergency services (police, fire-fighters, etc.) against fire, chemical and biological hazards was clearly identified as an important spin-off of military research as presented at the meeting. For the military aspects of this theme, many links to the operational requirements for special task units (reconnaissance, etc.) of the research were identified. Other observed themes were:

- The sharply increased use of manikins in clothing and threat (steam, fire) evaluation. Sweating manikins or body parts (hands, feet, head) were presented as recent developments.
- Successful development of personal cooling systems and the development of good evaluation methods.
- Use of spacer materials in heat protection, and for creating spacers for active cooling.
- Continued development of NBC protective clothing towards minimal heat stress, towards integrated (in combat suit) systems and towards materials with increased air permeability for the over-suit systems.
- The optimisation of heat and cold adaptation of soldiers before going on missions to respective areas.
- The successful use of models for prediction of heat and cold stress, survival time, frostbite risk, water requirements, clothing thermal performance, and for hypothesis testing.
- The development of new indices; for classification of physiological strain (heat and cold) and climate.

In the discussions a number of topics with interest from many countries were identified that may be considered in terms of future joint projects or meeting themes:

- Thermoregulatory fatigue.
- Inter laboratory comparison project on performance of dry and sweating thermal manikins.
- Creation of a (black-box) electronic climate analyser, using sophisticated heat balance analyses or even physiological models to transform the climatic measurements of the device into a simple heat stress index for use in the field.

This symposium covered a very wide area of research. Hence, the 43 papers presented here could only be a very selective representation of the whole research field. Though, especially with the excellent review papers, a good overview of the field was presented, the reader should keep in mind that for most topics only a single or perhaps two representative communications were present. This in some cases implied that for areas where controversy is present, only one view was presented at the meeting. This evaluation report attempts to put these papers in perspective, but the reader should bear this problem in mind when going through the original material.

Notwithstanding these remarks, the symposium provided an excellent overview of recent research and developments in this area and as was clear from the many discussions in and outside the meeting room it provided substantial food for thought and ideas for future work.

Given the speed of development in this area, a follow up symposium on the same topic would be valuable in three to five years. Special topic meetings as suggested above, would be relevant before that date.

Souffler le chaud et le froid: comment se protéger contre les conditions climatiques extrêmes

(RTO MP-076 / HFM-061)

Synthèse

Des spécialistes des pays membres de l'OTAN et du Partenariat pour la paix se sont réunis à Dresden, en Allemagne, du 8 au 10 octobre 2001, pour discuter des interactions entre le climat, les vêtements et les équipements, ainsi que de l'impact de la physiologie du combattant sur son état de santé et ses performances opérationnelles. En tout, 118 personnes originaires de 20 pays différents ont participé à la réunion, et 43 communications ont été présentées. Le programme des différentes sessions s'établit comme suit : "Les avancées dans les technologies vestimentaires," ; "les dernières technologies pour diminuer le stress thermique" ; "les avantages militaires d'une adaptation physiologique au chaud et au froid" ; et "la modélisation, le contrôle et les limites thermiques".

L'un des thèmes sous-jacents de la conférence a été l'intérêt marqué des intervenants pour la recherche en matière de lutte contre le terrorisme. L'optimisation de la protection des services d'urgence (police, pompiers, etc.) contre l'incendie avec prise en compte des risques chimiques et biologiques a été clairement identifiée, au cours de la réunion, comme une retombée importante de la recherche militaire. En ce qui concerne les aspects militaires, de nombreux liens avec les besoins opérationnels des forces spéciales (reconnaissance etc.) ont pu être identifiés. Les autres thèmes suivants ont été étudiés :

- L'utilisation fortement accrue de mannequins pour l'évaluation des vêtements et de la menace (vapeur, incendie). Des versions récentes de mannequins et de parties du corps factices (mains, pieds, tête) à exsudation ont été présentés.
- Le développement réussi de systèmes de refroidissement individuels et le développement de méthodes correctes d'évaluation.
- L'utilisation de matériaux séparateurs pour la protection thermique et pour la création de séparateurs pour le refroidissement actif.
- Le développement continu de vêtements de protection NBC, conçus pour limiter le stress thermique, l'intégration (dans les tenues de combat) de différents systèmes, mais aussi de matériaux plus perméables à l'air pour les systèmes portés par dessus les tenues de combat.
- L'optimisation avant le départ en mission dans certaines zones géographiques, de l'adaptation des combattants aux extrêmes climatiques.
- L'utilisation, avec succès, de modèles pour la prévision du stress thermique, des temps de survie, des risques de gelure, des besoins en eau, des performances thermiques des vêtements, et pour la vérification d'hypothèses.
- Le développement de nouveaux indices pour la classification du stress physiologique (chaud et froid) et du climat.

Lors des discussions, un certain nombre de sujets d'intérêt pour de nombreux pays ont été identifiés, lesquels pourraient faire l'objet de futurs projets ou thèmes de réunion conjoints, à savoir :

- La fatigue isothermique.
- Un projet entre laboratoires pour comparer les performances des mannequins secs et ceux à exsudation.
- La création d'un analyseur électronique de climat (du type boîte noire), mettant en œuvre des analyses sophistiquées de bilans thermiques, voire même des modèles physiologiques pour transformer les mesures climatiques de l'appareil en un indice de stress thermique pour utilisation sur le terrain.

Ce symposium a couvert un vaste domaine. Par conséquent, les 43 communications présentées ici ne sont qu’une représentation très sélective du domaine étudié. Néanmoins, et grâce surtout à l’excellente qualité des communications de synthèse, un très bon tour d’horizon a pu être réalisé. Le lecteur doit tenir compte du fait que seule une ou deux communications a pu être présentée pour chaque sujet et pour certains cas litigieux, un seul point de vue a pu être exprimé. Ce rapport d’évaluation tente néanmoins de placer ces communications dans leur contexte, et le lecteur doit en tenir compte en lisant l’ensemble des textes.

En dépit de ces remarques, le symposium a donné un excellent aperçu des travaux de recherche et des développements récents dans ce domaine, et beaucoup d’éléments de réflexion et d’idées pour les travaux futurs sont ressortis clairement à travers les nombreuses discussions qui ont eu lieu pendant et après la réunion.

Etant donné la rapidité des développements dans ce domaine, il est apparu opportun d’organiser un autre symposium sur ce même thème dans trois à cinq ans. Comme il est recommandé ci-dessus, il serait souhaitable également d’organiser des réunions de spécialistes sur ces sujets avant cette date.

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Technical Evaluation Report

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INTRODUCTION

On 8-10 October 2001, NATO and Partner for Peace nationals with military, commercial and academic backgrounds met in Dresden, Germany, to discuss the interaction between the climate, the clothing and equipment, and the physiology of the soldier in relation to its impact on the soldiers health and operational performance. The symposium was organised by the Human Factors and Medicine Panel (HFM) with Prof. Dr. Wulf von Restorff as local coordinator.
One hundred and eighteen people participated in the meeting, originating from 20 countries. They attended a total of 43 papers. Seven of these were from industry, 36 from research and testing institutions. There were four keynote papers, ten posters and 29 oral presentations.

Theme/Overview

Protecting the soldier against climatic extremes or thermal stress induced by work in insulating clothing has never been addressed in a generic military context by NATO. In 1993 the Aerospace Medical Panel of AGARD held a Symposium on ”Support to Air Operations under Extreme Hot and Cold Weather Conditions”. The former Defence Research Group of CNAD did, from time to time, address thermal protection, usually in the context of NBC protective clothing.
Despite the technological advances in weapons systems and platforms, military operations still remain ultimately dependent on the capabilities of the individual soldier. Extremes of heat, cold and reduced metabolic heat dissipation due to insulating clothing can seriously degrade these capabilities, put the soldiers life at risk, reduce his or her performance and ultimately will compromise mission success. Although clothing and equipment can be designed to provide optimal protection against climatic extremes, these protective items will often themselves degrade performance.
Over the last decade understanding of the physiological and clinical consequences of exposure to climatic extremes has advanced considerably. There have also been advances in clothing materials technology, which should lead to enhanced – and simplified – approaches to cold protection. Personal Cooling Systems (liquid, air, ice etc.) have been under development for nearly three decades, and appear to represent a good approach to protecting against heat apart from the related logistic problems. Also, improvements have been made in prediction of the consequences of exposure to thermal extremes. This information allows commanders to plan operations with a good estimate of the physiological risks involved and of the performance decrement to be expected.
This symposium provided an excellent opportunity to obtain an overview of available knowledge in this area and, given the high level of expertise of the attendants, to have a critical discussion of the implications for military operations.

Throughout the symposium, there was a noticeable influence on the discussions of the terrorist attacks in New York and Washington DC on September 11, 2001. As probably was the case with all military disciplines in this period, there was a need to discuss the relation between the knowledge presented here and the application of that knowledge in the fight of and defence against terrorism. Before discussing the content of the meeting, I would briefly like to discuss how the recent events affect the need for the expertise of the participants.
This discussion reflects remarks made in presentations as well as discussions between participants between presentations.

Though terrorism in itself isn't new, given the scale of the attacks and given the biological attacks afterwards one can state that a new threat has emerged, quite different from the well-defined 'classical' military threat:

- The current threats are present in home countries, without a declaration of war,
- As for the offensive targets one can recognise that they are:
    - Small; terrorist groups train and operate typically in small units;
    - The targets are located within 'civil' areas, which makes any attacks politically highly sensitive;
    - Targets are difficult to locate, therefore requiring small reconnaissance units;
    - Often located in extreme climatic conditions.

The home threat requires a discussion of protection of the civilian population. It can be expected that the coming years will bring about a risk-benefit analyses in relation to civilian bacteriological and chemical protection. More directly of relevance however is the protection of emergency services, as their risk, being called to problem areas, is much higher. For these groups, the basic requirements for heat, cold, and ballistic protection have not changed, but there is an increased need and renewed interest in higher level NBC protection with the consequent heat burden in these workers. The chemical attacks on the Tokyo subway system and the recent Anthrax scare show that protection for such threats is essential, though it may be limited to special units. Here we would expect to see a direct spin-off of military research as presented at the symposium and research in the protection area.
Regarding the point that counter-attack targets are often located in civil areas, and that the location of these targets will require small military units for reconnaissance, one can envisage that such units often cannot be reached with supplies. This implies that they will need to rely heavily on their equipment and their clothing. Considering the target location in more extreme climates, the latter needs to protect them from these climatic influences.
All these considerations above indicate the great importance of the topic of this meeting on 'Protecting Against Climatic Extremes', as well as its interaction with NBC protection, for the military, the emergency services, and, be it to a lesser extent, for the civilian population.

SYMPOSIUM PROGRAM

The overall symposium was chaired by Dr. (Col) John Obusek (US) and Dr. Wulf von Restorff (GE), with Dr. Michel Ducharme (CA), Dr. Hein Daanen (NE) and Dr. Kent Pandolf (US) as additional members of the programme committee, supported by Dr. Cornelius Wientjes (NE/F) as Panel Executive.
The symposium was split in 4 sessions, each starting with a keynote address. Due to travel restrictions related to the September terrorist attacks, 4 papers and one keynote were withdrawn.

After the opening ceremony (welcome address by Brig. Gen. Dr. E. Roedig (GE), Mr. Detlef Sippel (for the Dresden Mayor), Col. Dr. Willem Tielemans (on behalf of R&TO) and Col. Dr. John Obusek (for the organisers)), Dr. Manny Radomski (CA) presented the first keynote *'from pole to pole: a thermal challenge'*.

Session I, 'Advances in clothing technology' was chaired by Dr. K.J. Glitz (GE) and Dr. H. Daanen (NE). The keynote was cancelled (Uglene; CA), giving extra time for the 12 communications on the topic.

Session II, 'advanced technology for heat stress mitigation' was chaired by Dr. (COL) John Obusek (US) and Dr. M. Ducharme (CA). The keynote by Dr. H.J. Knöfel (GE) *'operational and thermo-physiological needs for metabolic heat dissipation: ways, deviations and progress'* was followed by 4 communications (3 others cancelled).

Session III,' military benefits of physiological adaptation to heat and cold' was chaired by Dr. K. Pandolf (US) and Dr. W. von Restorff (GE). The keynote *'Human adaptations to heat and cold stress' prepared* by Dr. M.N. Sawka was read by Dr. Obusek. This was followed by 6 communications, and a poster session with 7 posters.

Session IV, 'modelling, monitoring and thermal limits' was chaired by Dr. M. Ducharme (CA) and Dr. H. Daanen (NE). The keynote *'Heuristic modelling of thermoregulation, -basic considerations, potential and limitations'* was presented by Dr. A. Shitzer (Israel), followed by 7 communications and the technical evaluator's report.

The meeting was closed by the chair of HFM panel, Dr. (Col.) W. Tielemans (NE).

SUMMARY OF THE MAIN TRENDS AND RELEVANT DEVELOPMENTS

Advances in Clothing Technology

Spacer Materials

The presentations in this session and session II included actual developments in clothing as well as developments in measurement techniques of clothing properties. Some interesting innovations were presented, most related to possibilities for body cooling. They involved the use of spacer materials in the form of a 3D mesh (Just et al., [paper 13], Knöfel et al., [15]) and others in the form of spirals (Buckley et al., [paper 2]), creating an air gap or channels in the clothing to allow forced air-cooling. For the spirals various other applications were presented, as impact protection and creating an insulating vacuum space. In addition, both spacer materials may find use to alleviate the problems with reduced insulation due to wind (Holmér et al. [6]), as they could help to reduce the compression of the garment that occurs with wind exposure.
Nocker and Siebert [9] applied a spacer material to a fire-fighter garment and showed positive results in terms of heat protection and lower liquid absorption.

Chemical Protection and Heat Stress

In several papers on chemical protection, one could recognise the competition between 'protection' researchers and 'thermal' researchers. Protection researchers obviously are inclined to maximise this, whereas the thermal researchers warn for the reduced operational efficiency that goes with increasing protection levels (heat load, procedural load, weight of equipment). The latter advocate to sacrifice some of the protection to reduce heat stress. Against this background the papers presented showed efforts to minimise thermal stress within the current NATO protection requirement. A paper from industry (Töpfer et al., Kärcher GmbH [1]) showed an example of such optimisation. The presenters concluded that for an optimal balance between protection and thermal stress, integration of the

protection in the standard combat suit is essential, as this is the only way to reduce the number of clothing layers in the NBC protected state. Another paper dealt with a theoretical analyses of penetration of wind into the microclimate (Sobera et al., [7]), which is relevant for NBC protection too. This and Kaaijk and Brasser's [40] study on chemical protection at various wind penetration speeds and material air permeabilities lead the way to a theoretical understanding of how increasing air permeability can be used to reduce heat stress, while keeping up required protection levels.

In all presentations, it was obvious that the scientists involved can only optimise heat stress levels within the fixed protection requirements. As a message to the 'protection' people, it would be interesting to review the protection requirements. Are they still based on the scenarios we would deal with today? Do we need more differentiation? Emergency services may need different levels from military personnel given their deployment.
Any differentiation would allow further optimisation of the protection-heat stress balance.

Testing on Human subjects	Level 5	Large scale field trials (n>>100)	Cost & Effort
	Level 4	Medium scale, controlled field trials (20<n<100)	
	Level 3	Controlled laboratory testing (n<10)	
Testing on Equipment	Level 2	Use of predictive modeling and manikins for design and biophysical analyses of clothing ensembles	
	Level 1	Physical evaluation of clothing materials	
	Level 0	Analyses of tasks and general requirements	

Figure 1, development and evaluation stages of protective clothing.

Manikins

The next trend that one could recognise in this session was the shift in emphasis towards more basic clothing development and evaluation stages. In order to explain this, an overview of the typical process followed in design and evaluation of military and other protective clothing is presented in figure 1.

Typically research and development starts with level 0, analysing the tasks and the specific requirements. Next, materials are selected for the garments, using data on those materials like insulation, abrasion & tear resistance, colour fastness etc. These materials are then confectioned into garments, which are tested on manikins, and predictive models are used to predict their performance (psychrometric range)(level 2). Then, the tests on subjects start, from controlled lab tests (level 3) to full-scale field trials (level 5). The higher the level, the bigger the effort and cost to do a test. Level 5 tests are in practice only seen in the military and sometimes in fire-services and the police, as for most other professions the numbers of garments to be procured are too small to justify the cost involved in these large scale tests.
The papers presented [3,4,5,6,8,9,35,36] showed an increased interest and activity in the level 2 approach, using thermal manikins. It became clear that many more manikins have become operational in research labs across NATO countries in the last years and these are used more and more in evaluation projects. Further, a strong development towards sweating manikins could be seen, and interesting solutions were shown. Given this increased emphasis on level 2 testing some caveats need to be added: Those involved in procurements should not lose sight that in the end subject testing and the field test are essential to obtain the full story on a clothing system or equipment. An excellent example of such testing was presented by Warmé-Janville et al. [26], showing the use of an extensive test battery to evaluate protective clothing.

As for the manikin use, one should further realise that sweating manikin technology, though it clearly has a place in evaluations and comparative studies, is still in the early development stages and results do not yet represent real human sweating behaviour.

Besides a highly interesting overview of manikin history in the US (Endrusick et al, read by Pandolf [3]), sweating manikin evaluations were presented by Richards and Mattle [4] (a manikin with a very natural movement pattern) and Warmé-Janville et al. [36] as a general tool for comparative investigations and by Warmé-Janville and Pélicand [35] for glove and by Uedelhoven et al. [10] for footwear evaluation (the latter showing a beneficial effect of thick sock shat for moisture transport away from the foot). These presentations demonstrated the potential value of such evaluation tools within the earlier mentioned limitations. Camenzind and den Hartog [5] presented an interesting study on the use of a sweating cylinder for the study of moisture accumulation in sleeping bags. They showed that condensation was inversely proportional to the bags insulation. One criticism to the graphically presented results was that by choosing a low cylinder weight (lower than human) resulted in a lower compression of the sleeping bag materials than normal which typically gives down filled bags an advantage in the results that would probably disappear at realistic body weights. Also the unnatural shape of the cylinder versus the body in relation to compression of the sleeping bag materials should be considered.
Holmér et al. [6] showed with moving (dry) manikin measurements that clothing insulation decreases dramatically at high wind speeds, the decrease being related to the clothing's air permeability. He warns that these decreases should be incorporated in the prediction modelling to prevent large errors in risk assessment.

Desruelle et al. [8 and 34] demonstrated the use of a physical test apparatus and a water circulated manikin for testing of clothing's protection against hot steam jets (navy), showing the relation between thickness, vapour permeability and protection. In the discussion phase change materials were suggested as possible solution for this specific (one-off) problem, where they may show more potential than for most other applications.

Advanced Technology for Heat Stress Mitigation

The human has a tremendous adaptive capacity for work in the heat as discussed by Dr. Sawka in the next session. The keynote of this session, by Dr. Knöfel reviewed the classical literature on heat exchange between body and environment and analysed its importance for heat loss through cooling systems in those cases where the normal adaptive range of the human does not suffice. In first instance the remedy is to optimise clothing properties for heat loss, but the next stage is the use of active cooling systems. After a review of the possible methods (reflective garments, cooling garments with gels or ice packs, compressed air systems, systems with circulating liquid etc) Knöfel concludes that the best general approach is that which allows the body to thermoregulate using its sweating system. In essence this implies cooling with air streams across the skin. In the discussion, it was emphasised that the choice for a certain cooling principle is often dependant on logistic requirements. Compressed air is not always available and if available usually limits the movement range of the person using the system.

The following papers by Just et al. [13] and Knöfel et al. [15] presented an interesting example of an air cooled suit (GKSS and GUSA flight suit) and helmet. The suit development showed strong similarities with those done in the Soldier Modernisation Programme. Instead of multiple layers each with their own function, an integrated approach was chosen providing a suit with high useability and integrated cooling properties. In the demonstration of the equipment after the presentations it became clear that helmet and suit integration/compatibility was not yet optimal, showing that in the ideal approach the helmet-suit system should have been developed together as well. So, though good developments, these problems underline the need for 'total concept' development. This should be

another reminder to this matter for those involved in the SMP (Soldier Modernisation Plan) development.
Discussion of these papers pointed towards a greater cooling potential that might be achieved with the suit than currently present by optimisation of the airflow patterns.
Maier-Laxhuer et al. [16] presented a Zeolite system, which can provide a regeneratable cooling source for such applications.
Finally Warmé-Janville et al. [19] showed an extensive and thorough evaluation of various cooling systems. They showed that rankings of systems can be based on a large number of performance characteristics, e.g. cooling power, cooling per power input, cooling per weight, negative impact on failure etc. Where the review discussed earlier promoted air-cooling systems if one has the choice, it is obvious that the choice for a cooling system is often limited by operational circumstances. In those cases one needs to be able to select the best system for those circumstances and information for this was provided in the study presented. Some questions were asked regarding this paper, on whether assessment parameters could be integrated into a single performance value for the systems. This can only be done for a single application however, as for each different one the weighting factors of the various performance parameters should be different depending on the specific circumstances (availability of power, freedom of movement etc.). Otherwise important information would be lost with such an integrated performance parameter.
Papers 14, 17 and 18 were withdrawn.

Military Benefits of Physiological Adaptation to Heat and Cold

This topic was already introduced on day one with the review by Radomski, who demonstrated the physiological adaptations to cold present in various populations. Further he presented data on a study in which soldiers were pre adapted to cold by taking cold baths in the period before they were sent to the Arctic. The study clearly showed advantages of the pre adaptation procedure, which resulted in less cold induced diureses and a reduced shivering response. This information on cold adaptation was supplemented by an excellent review by Sawka, demonstrating the high adaptive capacity to heat the human possesses. Various aspects of acclimatisation were discussed: improvements in sweating system, cardiovascular stability, and central changes. For the cold, data presented by Sawka did not support adaptation as strong as they did for the heat. For the cold, results found in literature are more often conflicting. Both keynotes emphasised the need for good preparation of the troops before being sent to hot or cold areas and also showed that operational capacity is far from 100% on arrival if such factors are not taken care of.
For the cold the conclusion was that physiological adaptations to cold are possible (metabolic or insulative response), but these are quite limited. Hence the way forward is risk prediction, clothing optimisation and if possible active systems that help maintain thermal homeostasis. On cold exposure the short-term goal is to maintain dexterity [20, 21], and the obvious long-term goal is to avoid hypothermia [11, 12, 22]. In the communications this was discussed for immersion clothing where Ducharme [11] presented tests on a new concept of immersion suits. In order to reduce the heat stress experienced in the suit, a new design was applied, which allowed the openings at wrist, neck etc to remain open while not in the water. The protective capabilities of the suit were tested during immersions at sea and found to meet the requirements. Brooks et al. [12] tested the knowledge of survival course participants on hypothermia and proper use of the immersion suits. Though the knowledge had improved after the course, participants still did not score anywhere close to 100 percent. Given that some of the questions asked to the participants could have been considered leading to the right answer, this is a worrying result and emphasises the importance of evaluations of training programmes.

Brajcovic and Ducharme [20] compared various methods of warming the body and the hands in terms of their efficiency in maintaining manual dexterity. They showed that maintaining a warm core (trunk) overall produced the best results in terms of dexterity and hand skin temperature. Though these can be considered the most relevant parameters, they are not the only System Performance Indices that may

be used, however. In the discussion the question was put forward which warming method would be best for a given amount of heat input. This is relevant if for instance only battery power is available. This question needs further investigation. Other questions related to differences in effect on fine versus gross dexterity; on system weight, on weight/efficiency; and on the possibility of continuous work without interruption for donning/doffing the system. The latter typically being a problem with gloves.

Rintamäki et al. [21] demonstrated the additional cooling effects when hands are exposed to and wetted by snow, an effect that is often not included in thermal models. Castellani et al. [22 & poster 38] (read by Pandolf) presented the concept of thermoregulatory fatigue. They showed that exhaustive exercise will lower cold tolerance, probably due to a blunted vasoconstriction response. This results in an increased heat flow from the body to the environment and this loss increases the risk of hypothermia.

Goderdzishvili et al. [23] and Chaduneli et al. [24] presented data on the interaction between cold exposure, altitude exposure, and smoking in the Georgian army, demonstrating the ill health effects on lung and blood clotting function. The session was closed by Montain. et al. [25 & poster 39] (read by Obusek) presenting a paper on the risks of hyperhydration, causing hyponatremia with life threatening complications. The paper presented new guidelines for water requirements based on modelling and on field experiments. Where the old guidelines were based on the hourly work time and climate, the new guidelines are based on climate and actual workload and they also include upper limits for water intake.

Modelling, Monitoring and Thermal Limits

Models

The keynote in this session by Dr. Shitzer (ISR) gave an extensive overview of the various uses of thermal models. Starting with the question ‘Why should we bother with a model?’ he presented various approaches and showed how models can be helpful in various ways as e.g. saving experimentation time; selecting ‘best discriminating’ conditions for experiments, and extrapolations to situations for which experimentation would be ethically unacceptable but which may occur in real life. Dr. Shitzer closed his paper with an overview of area’s for future work in modelling research:

- detailed investigation of control functions for blood flow,
- alternative solution techniques saving computer time,
- clothing: what are the actual heat transfer processes occurring,
- to use a multidisciplinary approach, and an area added in the discussion:
- individualising the models for specific groups (aged, genders, etc.).

In the rest of the session, and also on the other days, various examples of the development and application of models were presented:

- Montain et al. [25] showed how modelling (USARIEM models on water requirement) can reduce the number of evaluation tests needed;
- Danielsson [28] showed an elegant study of the use of an improved Wind Chill Index (WCI) model in the prediction of the risk of skin freezing, adding the previously absent effects of solar radiation, humid skin and habituation to cold to the old WCI model approach and thereby improving the quality of the risk prediction (in the discussion a comment was made that the assumption that CIVD (Cold Induced Vaso-Dilation) is always present could result in an underestimation of risk);
- Camenzind and den Hartog [5] predicted application ranges of sleeping bags, using a simple model based on the principles of that developed by Farnworth, using material measurements for top and bottom sides; -Holmér and Nilsson [6] presented an empirical model that can be used to predict loss of clothing insulation due to wind and movement, taking clothing air permeability into account; and finally Mäntysaari et al. presented data that can be used to model sweat accumulation in clothing during interval exercise in the cold, demonstrating that the type of work/rest cycle has a strong influence on sweat accumulation giving the advantage to short work/rest cycles as sweat peaks are smaller then.

Monitoring and Thermal Limits

In the second part of this session, Markou et al. [29] (presented by Dr. Diamantopoulos) discussed the evaluation of a heat stress index to be used by the Hellenic air force. So far they worked with the ‘discomfort index’. The authors discussed that application of WBGT and more recently of the FITS: the ‘Fighter Pilot Index of Thermal Stress’. They see clear improvements by the implementation of FITS, but also conclude that this index needs some adjustment to the specific situation of the Hellenic forces.

Pandolf and Moran [30] presented two strain indices, one for the heat (the Physiological (heat) Strain Index, PSI) and one for the cold (Cold Strain Index, CSI). These are not predictive indices, but indices that integrate a number of physiological responses in a single index value. For heat this is a weighted sum of the heart rate and of the core temperature response, both expressed as fractions of the difference between resting and maximal values. For the cold, this is a weighted response of the change of body skin and core temperatures from ‘resting’ values again expressed as fraction of the difference between resting and limit values. Hence the latter is an alternative way of expressing body heat deficit relative to set limit values. The indices, especially the PSI have been tested on a number of datasets, and they have been shown to discriminate well between stress conditions. In the discussion, the problem of individual differences was mentioned: during heavy work, a fit person would reach heat exhaustion at a higher PSI (both high core temperature and high heart rate) than an unfit person (high heart rate at still low core temperature). Hence the meaning of a certain PSI value is different for different individuals. The authors (also of [31, 32]) suggested that, for instance where the PSI is used for personal heat stress monitoring, it should be individually calibrated.

An application of PSI in personal monitoring systems was demonstrated by Hoyt et al. [32] (presented by Obusek), where PSI was used to integrate heart rate and body core data (as measured using a radio pill). These data were then transmitted to a base station, allowing the commanders to monitor the physiological status of the individual soldiers. This promising technique is in development to improve reliability and to reduce intelligibility of the radio signals by unfriendly forces.

Moran et al. [31] discussed a possible integration of the PSI with a new climatic index: the ESI (Environmental Stress Index). They showed the deduction of a new ESI index producing highly similar values as the WBGT index, but based on more commonly measured climate parameters (temperature, relative humidity, solar radiant flux) than those for the widely used Wet Bulb Globe Index. Despite not including the wind speed in the new index they observed a high correlation

between ESI measurements and WBGT measurements for data of several Israeli weather stations. There are several points that may need further research before full acceptance of this index, however:

- The good correlation despite the absence of wind in the new index may point towards problems of wind sensitivity of WBGT itself, or to the use of specific combinations of climatic conditions in the evaluation where wind has had little impact.
- Using relative humidity instead of vapour pressure (the driving force for evaporation; easily calculated from the climatic data) in the equation results in a negative regression coefficient for this factor that is statistically correct, but intuitively opposite from what is expected. Using vapour pressure (calculated easily from temperature and relative humidity) would likely improve this.
- Finally, in the discussion the point was raised that with the arrival of small electronic devices, as pointed out by Dr. Moran as the bases for the new index, which can measure climatic parameters it may be time to discuss in the scientific community whether one should hold on to the widely used, but proven to be flawed, WBGT index or to similar ESI in its current form (perhaps better named WBGT*). The alternative would be to use this opportunity of electronic development to make a step to more complex indices and models that could be put in a black box (microchip) as far as the user is concerned and could deliver more accurate results. The 'wristwatch' size devices suggested by Dr. Moran would form an excellent basis for this.

As for the link between ESI and PSI, Dr. Moran provided an example of a work rest-cycle table using the heart rate component of PSI. He showed how information relating to these indices could be given to operational planners.

General Observations

In addition to the specific discussions presented above, there was also a general theme present in many communications: the importance of proper education. With the continuing development of specialised clothing and equipment it is paramount that soldiers and commanders are trained in the proper use of such clothing and equipment. This seems obvious, but in practice clothing and equipment are often used in different ways than intended by the design team, often causing loss of protective properties. It has to be communicated to the user why certain choices in clothing design were made, and how these affect function.

Also in other areas the education aspect is relevant. Brooks et al. [12] showed that even after a survival at sea training knowledge of participants on proper use of survival suits was not flawless, showing the need for constant improvement of teaching methods and courses. The paper of Montain et al. [25] showed that education on the need for rehydration has been successful, to the point where an overshoot was reached and individuals started to over-hydrate leading to hyponatremia casualties. Guidelines are now adjusted to take this risk into account.

Joint Projects

In the discussions a number of topics with interest from many countries were identified that can be considered in terms of future joint project:

- Thermoregulatory fatigue: the interaction between exercise exhaustion and thermoregulation and cold defence needs further study which could benefit from a multinational approach;
- Given the great interest in manikin studies this forms an important topic. First inter-laboratory comparisons studies have been performed for dry manikins recently for the civil market, but should also be performed between NATO labs. Even more in the centre of attention are the sweating manikins and sweating body section models (feet, hands, heads). While the technology of dry manikins is converging towards realistic anatomical shapes and full surface temperature measurement and heating, that of sweating manikins is highly variable between labs [3, 4, 5, 10, 35, 36). They use different ways of producing vapour (e.g. direct vapour injection or water infusion to surface 'sweat glands' or pre-wetting of a textile skin layer), and

show very different sweat gland distribution. Most of them are, as discussed earlier, used for comparative measurements but the ultimate goal obviously is to imitate human sweating. Initial comparative tests between labs have illustrated the high variability in results due to these differences. A multi-country/multi-laboratory project on this topic would ensure that resources would be used optimally, and a good knowledge of differences between different approaches would be obtained.

- With the discussion of the new Environmental Stress Index, the time may be right to start a joint project for the creation of a (black-box) electronic climate analyser which would use sophisticated heat balance analyses or even physiological models to transform the climatic measurements of the device into a simple heat stress index for use in the field which eventually could replace WBGT.

CONCLUDING REMARKS

This symposium covered a very wide area of research. Exposure to heat and cold, together with its health effects and the role of clothing and equipment in alleviating or amplifying ill effects of heat and cold stress is investigated from numerous angles. Hence, the 43 papers presented here can only be a very selective representation of the whole research field. Though, especially with the excellent review papers, a good overview of the field was presented, the reader should keep in mind that for most topics only a single or perhaps two representative communications were present. This in some cases implies that for areas where controversy is present, only one view was presented at the meeting. This evaluation report attempts to put these papers in perspective, but the reader should bear this problem in mind when going through the material.

Notwithstanding these remarks, the symposium provided an excellent overview of recent research and developments in this area and as was clear from the many discussions in and outside the meeting room it provided substantial food for thought and ideas for future work.

ACKNOWLEDGEMENTS

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From Pole to Pole –
A Thermal Challenge

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Summary

The issues of thermal physiology, protection, modeling, survival, and injury have been addressed in thousands of publications over the decades, and the topic of thermal protection and survival has been the subject of several NATO DRG and AGARD symposia. Therefore, rather than review the current state of the art of the field which is the subject of the many papers that will be presented at this Symposium, this paper re-examines some of the pioneer work in cold physiology that has laid the foundations of our current understanding as to how humans have adapted to severe cold climates, often without modern technology or clothing. Scholander, Hammel, Elsner, Andersen, and Hart are some of the scientific pioneers that have provided evidence from field trials that a variety of physiological adaptations can develop in the human species exposed to different climatic extremes ranging from one Pole to the other Pole. From these classical field studies, several different types of cold acclimatization of native races were identified. This paper reviews how some of these acclimatizations can be or have been applied to modern man. In conclusion, it appears that a rapid technique using intermittent exposure to severe cold for inducing cold adaptation or cold habituation does exist and does induce beneficial effects in soldiers required to subsequently perform and sleep under arctic conditions. It appears to be a hypothermic type of adaptation and eliminates the negative effects of cold diuresis. Furthermore, this technique appears to persist over a significant period of time even in a temperature environment making it even more of a desirable military technique. One sees a shift of the shivering threshold to a lower temperature, a shorter period of adaptation, and an increase in cold tolerance. It appears to be more akin to the type of adaptation demonstrated by the Australian aborigine and Kalahari bushman, that is, an Insulative Acclimatization.

Introduction

The issues of thermal physiology, protection, modeling, survival, and injury have been addressed in thousands of publications over the decades, and the topic of thermal protection and survival has been the subject of several NATO DRG and AGARD symposia (Table 1).

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

TABLE 1. List of DRG and AGARD Reports and Symposia on Operations in Extreme Thermal Environments

Borg, A and Veghte JH	The physiology of cold weather survival	AGARD-R-620 1974
Lorentzen, FV	Cold: physiology, protection and survival	AGARD-AG-194, 1974
Boutelier, C	Survival and protection of aircrew in the event of accidental immersion in cold water	AGARD-AG-211, 1979
Brooks, CJ	The human factors relating to escape and survival from helicopters ditching in water	AGARD-AG-305(E) 1989
AGARD Conference, Victoria, Canada, 1993	The support of air operations under extreme hot and cold weather conditions	AGARD-CP-540, 1993
NATO RSG-20	Handbook on predicting responses to cold exposure	AC/243(Panel 8) TR/20, 1995

Therefore, rather than review the current state of the art of the field which is the subject of the many papers that will be presented at this Symposium, this paper will re-examine some of the pioneer work in cold physiology that laid the foundations of our current understanding as to how humans have adapted to severe cold climates, often without modern technology or clothing.

Adventure, economics, national security, athletics, and scientific curiosity have been major motivating forces behind man venturing into such inhospitable climates as the Arctic and the Antarctic, particularly since man has evolved as a tropical animal. But certain civilizations have existed in such environments for decades with no modern technology. Beginning with Darwin during the voyage of the Beagle in 1831 (Moorehead, 1969), and subsequent explorers, scientists have been driven to investigate how such populations adapted to their harsh environments and survived. The foundations of our knowledge as to how man can adapt physiologically to different thermal environments (Figure 1) were laid by the studies carried out on the:

- Australian Aborigines,
- Kalahari Bushmen,
- Alacaluf Indians of Tierra del Fuego,
- Arctic Indians and Eskimos, and
- nomadic Lapplanders.

Scholander, Hammel, Elsner, Andersen, and Hart were some of the scientific pioneers that provided evidence from field trials that a variety of physiological adaptations can develop in the human species exposed to different climatic extremes ranging from one Pole to the other Pole. From these classical field studies, several different types of cold acclimatization of native races were identified. This paper will review some of these earlier studies and how some of these acclimatizations can be or have been applied to modern man.

Figure 1. Native groups studied by early investigator

Australian Aborigine

One of the first native groups investigated were the aborigines of central Australia who have existed in a semi-desert environment with average nightly temperatures of 4°C with a high radiant heat loss (Scholander et al. 1958). Their sleeping habits consisted of lying naked between two small fires. This then was a group intermittently exposed to periodic cold. The aborigines were described by FitzRoy as “the lathy thinness of their persons, which seemed totally destitute of fat, and almost without flesh...” (Moorehead 1969). This, then, was a race devoid of any peripheral body fat to provide any insulation (Figure 2).

The standard techniques used by Scholander and his colleagues (1958) to perform field evaluations of the metabolic and thermal responses to cold of these and subsequent native groups consisted of measuring the thermal and metabolic responses of the natives sleeping in a tent for an 8-hour period on a cot lightly covered with a blanket at an air temperature of about 3°C. Oxygen consumptions, rectal and skin temperatures were monitored continuously and the data compared to the responses of a control group of white subjects, usually the investigators themselves.

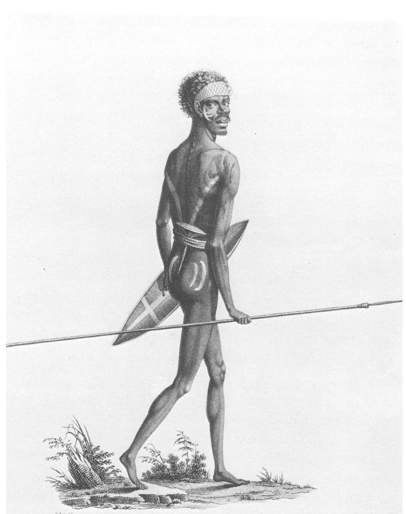

Figure 2. Australian aborigine.

Significant differences in the metabolic and thermal responses were found between the aborigines and the white controls. The controls responded typically by elevating their metabolic rates above basal by about 28 %, accompanied by drops of about 0.8°C in rectal temperature (Tre), 1.5°C in mean body temperature (Tb), and 2.4°C in mean skin temperature (Tsk) over the 8-hr period with bursts of shivering and disturbed sleep throughout the night (Figure 3, Panel A).

The metabolic and thermal responses of the aborigines differed significantly from the white controls, as the aborigines did not increase their metabolic rate, but in fact, experienced a decrease of about 7-8 %. This was accompanied by a greater drop in rectal temperature, almost 2-fold greater than the control, along with significantly greater drops in mean body and mean skin temperature of (Figure 3, Panel B). The natives slept comfortably with little shivering.

These findings led the investigators to propose the existence of an ***Insulative Acclimatization*** in the aborigines although it could also be classified as a ***Hypothermic Insulative Acclimatization.*** Further experiments in different seasons on a group of tropical aborigines not exposed to cold during sleep demonstrated the persistence of such an acclimatization supporting the concept that this was a racial characteristic.

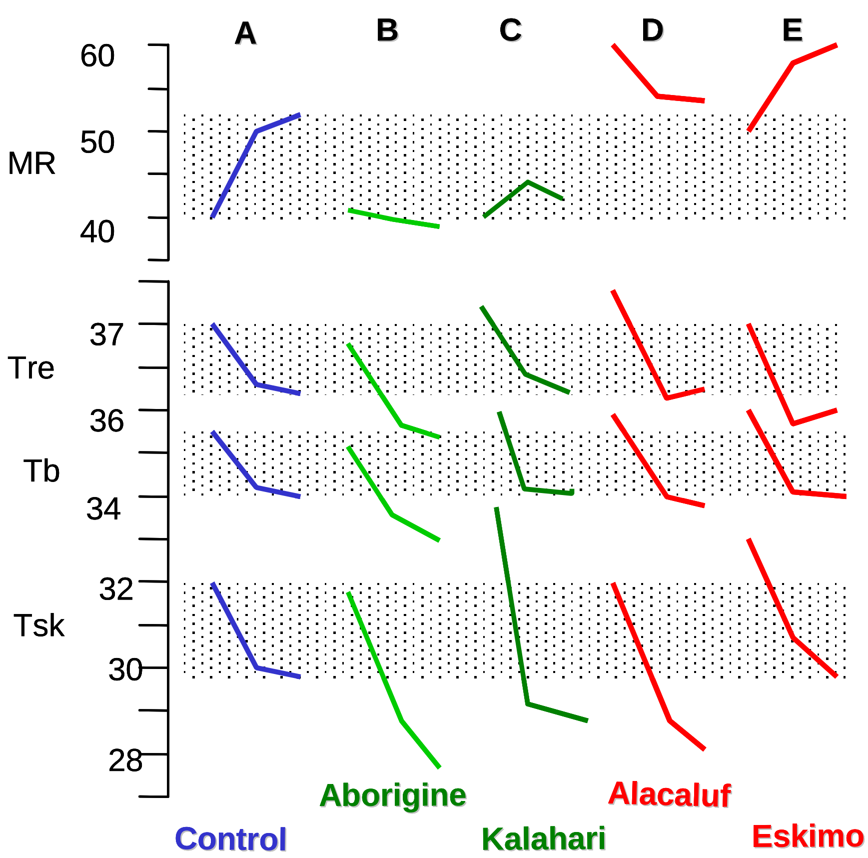

Figure 3. Comparative responses to a standard cold field test of different native populations.

Kalahari Bushmen

A Bushman’s body is the product of a million years of hunting-gathering life in the Kalahari climate. As he moves across the Kalahari, his heart must increase flow rate 8-fold when he runs across the desert at top speed. His heart has evolved into a machine more efficient than any man has ever designed. Bushmen can carry loads equal to their own weight and travel over the desert for hours without visible fatigue.The Bushmen of the Kalahari Desert wear little or no clothing and are rather small and lean with a resultant larger surface area per unit weight (Figure 4). Although their body build reflects the demands of the hot desert to shed heat more efficiently during the day, they are exposed to overnight cold down to 0°C in July making their body build a disadvantage without other compensatory mechanisms. One Bushman camp was described thus: “They had burned all their firewood the night before, and now it was too cold to go for more, or even go for food - so they sat cold, hungry, thirsty, and even tired, since they had been too cold to sleep during the night.- waiting with infinite patience - for noonday when the sun would give a little warmth”.

Figure 4. Kalahari Bushman

Wyndham and Morrison (1958) and Hamel and coworkers (1962) found that when exposed to cold overnight, the Bushman’s responses were similar to those of the aborigines of Australia. They did not shiver, showed little increase in metabolic rate over 8 hours, with rapid drops in body temperature, but not as low as that of the aborigine (Figure 3, Panel C). They appeared to rely on ***Insulative Acclimatization*** to survive in the cold.

Alacaluf Indians

Darwin during the voyage of the Beagle was one of the first scientists to become fascinated with the Alacaluf Indians of Tierra del Fuego (Moorehead, 1969). He described the climate of Tierra del Fuego as an appalling climate, one of the worst in the world. The cold exposure of the Alacaluf differed from that of the Australian aborigines and the Kalahari Bushmen in that the Alacaluf were exposed to a cold climate throughout the 24-hour day, and not just at night when they slept. On catching sight of the natives, his first thought was how much closer they were to wild animals than to civilized humans. (Figure 5).

“They were huge creatures...the trunk of the body is large, in proportion to their cramped and rather crooked limbs” who went naked except for a guanaco skin over their shoulders. “It was marvelous the way they could stand the cold. One woman who was suckling a baby came out to the Beagle in a canoe, and she sat there calmly in the tossing waves while the sleet fell and thawed on her naked breast. On shore these people slept on the wet ground while the rain poured through the roofs of their crude skin huts”. It was obvious that this tribe had adapted physiologically in some manner to the extreme climate with very little in the way of protective garments.

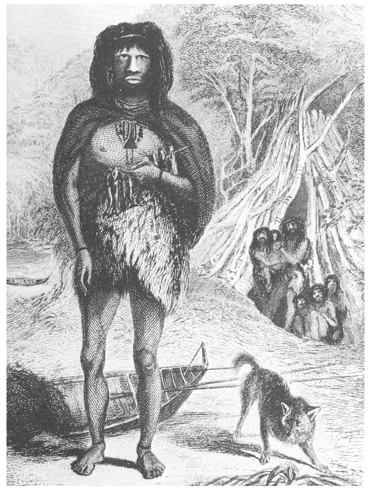

Figure 5. Alacaluf Indian (from Moorehead, 1969)

A team of scientists led by Hammel (1960) studied the metabolic and thermal responses of the Alacaluf during a night of cold exposure sleeping on a canvas cot in an unheated tent for 8 hours. They found that the Alacaluf had a resting metabolic rate about 160% higher than the white controls, which remained higher than the final elevated rate in the white controls. No other significant differences were evident between the two groups in rectal, body and skin temperature except for warmer toes in the Alacaluf, which were 2°C to 3°C higher than the controls (Figure 3, Panel D). They also had an undisturbed sleep in such a climate whereas the control subjects experienced difficulty sleeping due to the cold. As noted by Darwin, “at night they sat tgether round the campfires, the sailors shivering in the bitter cold, the Fuegians sweating in the heat of the fire”. This pattern of thermal responses was called ***Metabolic Acclimatization***.

Arctic Indians and Eskimos

Figure 6. Eskimos with bare extremities, but with excellent whole body insulation.

The Arctic Indians of the Yukon and the Arctic Eskimos were studied by Irving (1960), Elsner (1960) and by Hart (1962). (Figure 6). The normal pattern of cold exposure of the Eskimo and the Arctic Indians consisted of exposure to intermittent exposures to severe cold while traveling, hunting and trapping and sleeping in cool environments on the trail. Otheerwise, they were very well protected having developed an ideal Arctic clothing. Normally, during the day, the extremities were only exposed to the cold (Figure 6) and this is where the Eskimo stands out in terms of physiological adaptation. This native population showed responses similar to that of the Alacaluf, but with initial resting metabolic rates lower than the Alacaluf but significantly higher than the controls. However, whereas the initial metabolic rate decreased slightly during the cold test in the Alacaluf, it increased in the Eskimo to levels comparable to the Alacaluf (Figure 3, Panel E). The pattern of acclimatization exhibited by the Eskimo appeared to be more of a ***Metabolic Acclimatization*** although they demonstrated superior acclimatization of their exposed extremities.

Surprisingly, another Arctic population, the nomadic Lapps, with a life style similar to the Arctic Eskimo demonstrated a response that was more comparable to the Australian aborigine than other Arctic natives, that is, no increase in metabolic rate and a large drop in rectal temperature, reflective of a **Hypothermic Insulative Acclimatization** (Andersen et al. 1960).

Summary of Findings on Native Populations

These different modes of acclimatization to the climate become more distinct from a plot of the metabolic responses of each of the above groups as a function of their mean body temperature (Figure 7). By comparing the average metabolic response of each of the groups above as a function of their mean body temperature, two distinct patterns of cold acclimatization were evident, Metabolic Adaptation, and Hypothermic Insulative Adaptation. The typical unacclimatized North American or European demonstrated a low basal metabolic rate which increased markedly as body temperature decreased. Characteristic of a Hypothermic Insulative Adaptation, the Australian aborigine and the Kalahari Bushman had an initial metabolic rate similar to the white control, but one which decreased or did not change as body temperature decreased. A Metabolic Adaptation was evident in the Alacaluf Indian who began with a high resting metabolic rate which declined slightly with a falling body temperature; and the Arctic Indian and Eskimo with a metabolic rate intermediate between the Alacaluf and the control which increased as body temperature decreased.

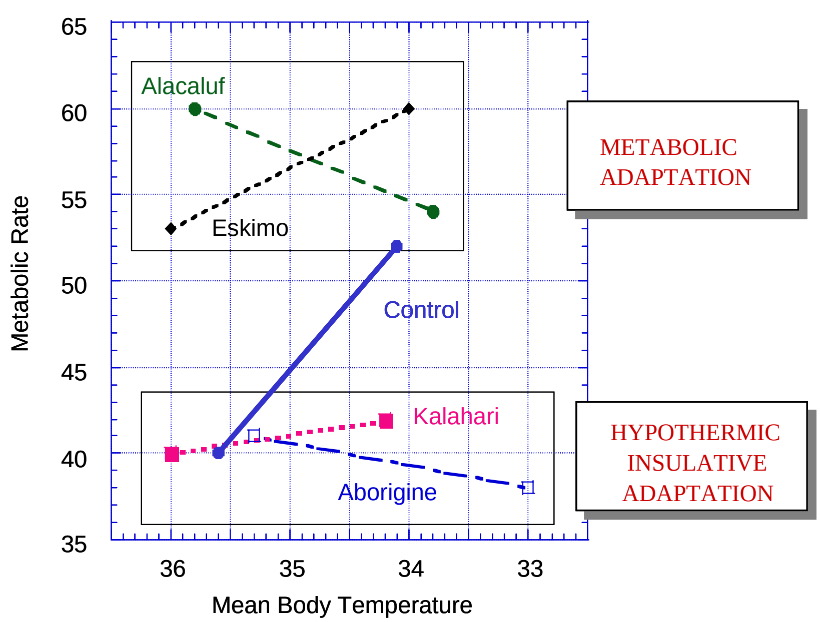

Figure 7. Heat production as a function of mean body temperature before (left points) and after the standard 8 hour cold exposure test..

LABORATORY/CHAMBER STUDIES ON ANIMALS AND HUMANS

The question subsequently pursued by investigators, partially driven by military requirements, was whether acclimatization to cold could be induced in a normal north american/european population, what type of acclimatization, and how quickly in order to have any practical military value. Therefore, it was necessary to try to relate these field studies of native populations to studies on both laboratory animals and humans in climatic chambers where the various variables could be controlled, including diet.

Approaches to Cold Adaptation

The experiments of LeBlanc's and Carlson's groups on animals exposed to cold were key to our understanding of the mechanisms of cold adaptation and the role of the autonomic nervous system in our responses to cold temperatures. From their work, two types of adaptation to cold were demonstrated in rats (Figure 8):

a) Metabolic Adaptation resulting from continuous exposure for weeks to moderate cold (6°C), and

b) Hypothermic Insulative Adaptation resulting from a series of intermittent exposures to severe cold (-20°C).

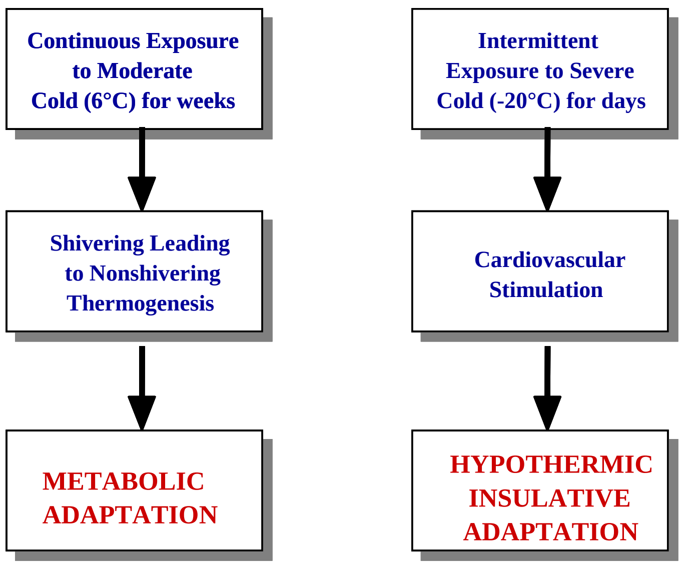

Figure 8. Types of adaptations induced in animals.

The mechanisms by which these two types of adaptation occur differed. Metabolic adaptation required a continuous prolonged exposure to moderate cold (ca. 6°C) over weeks and was characterized by an increased urinary excretion of noradrenaline (Fig 9A) and an increased noradrenaline sensitivity (Fig 9B; adapted from Leduc 1961, and Hsieh and Carlson 1957). These findings by Leduc and Hsieh and Carlson were key to our understanding of the mechanisms of cold adaptation and of the role of the autonomic nervous system in the responses of animals to cold. Also, during these changes, shivering was gradually replaced by a non-shivering mechanism of heat production.

However, as pointed out by Leblanc (1975), however, it is rare that modern man is exposed to continuous cold, and that intermittent repeated exposures are more the norm. A simple method of developing cold adaptation in a short period of time would have greater military value. LeBlanc, in fact, carried out a series of studies to examine the effects of short-term repeated periods of exposure to more severe cold (IS) to assess whether an increased tolerance and adaptation to cold could be induced in a much shorter time, hours and days instead of weeks (1967).

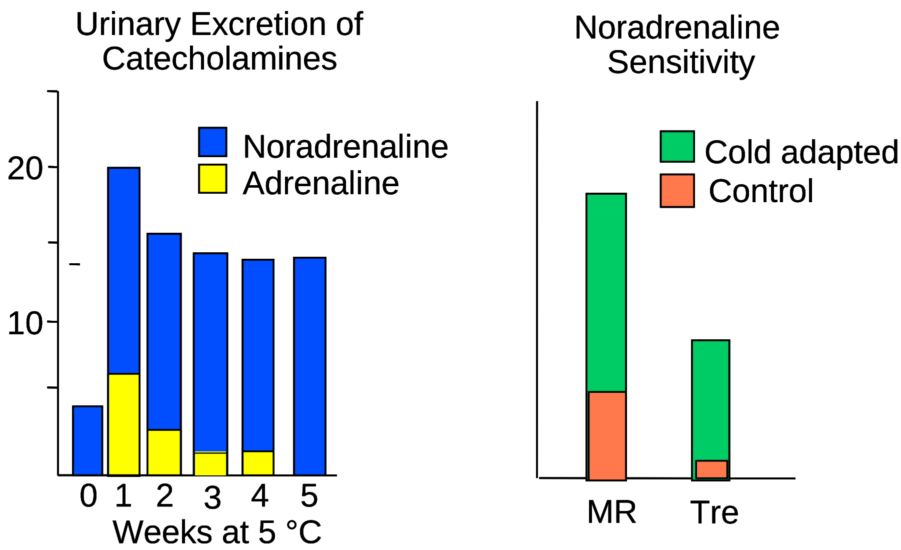

Figure 9 . Left panel shows the pattern of urinary excretion of noradrenaline and adrenaline during adaptation to moderate cold for 5 weeks, and the right panel the response of oxygen consumption (MR) and rectal temperature (Tre) in control and cold-adapted animals to noradrenaline infusion. Adapted from adapted from Leduc 1961, and Hsieh and Carlson 1957).

From his experiments on mice, he showed that although there was some increase in noradrenaline and adrenaline excretion during three days of repeated exposures to severe cold, the sensitivity to noradrenaline infusion on oxygen consumption was significantly different (LeBlanc et al. 1967). The normal increase in oxygen consumption observed in chronically adapted rats during noradrenaline infusion was not evident in the IS adapted rats (Figure 10). Thus, whereas the rats chronically exposed to moderate cold (CM) demonstrated characteristics of metabolic adaptation, the IS rats did not exhibit any increase in oxygen consumption, similar to the Kalahari bushmen and the Australian aborigine. Furthermore, he showed that the colder the temperature that the mice were adapted to by the IS technique, the better their survival times at different temperatures.

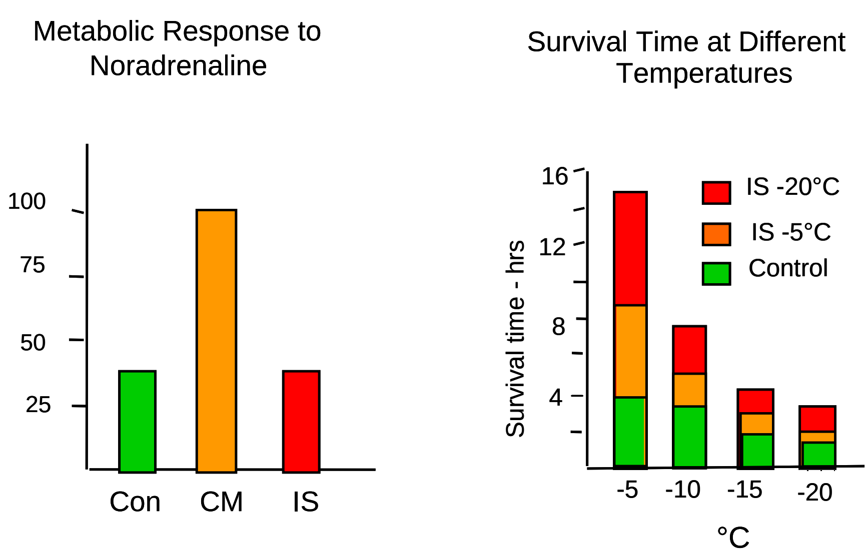

Figure 10. Response in oxygen consumption to noradrenaline infusion in control rats (Con), in rats chronically exposed at 10 °C for 6 weeks (CM), and in rats adapted to intermittent stress (IS) (9 exposures per day for 10 min each at –10 °C for 3 days). Survival times at different temperatures of rats adapted to cold by intermittent exposures to –20°C and –5°C are shown in the right panel.

Field and Laboratory Studies on Humans

A variety of approaches have been investigated to improve human cold tolerance and acclimatization. A partial summary of the three major approaches investigated in earlier studies are shown in Table 2. These have involved natural exposure to external climates, exposure to cold air in climatic chambers, and repeated immersions in cold water or cold air.This review will next examine two of the natural acclimatization studies in more detail and the application of the Boutelier technique for adaptation by exposure to intermittent severe cold in more detail.

Table 2. Methods of Acclimatization

Method	Conditions	Investigators
Natural exposure to external climate	Clothed men in the Arctic engaged in outdoor activities for up to 12 hr/day for 6 weeks	LeBlanc 1956
	Camping for 6 weeks in mountains at 3 to 5 °C	Scholander 1958
	Seasonal changes from Oct to Feb, 1 hr/day/month exposure in nude to 14 °C.	Davis and Johnston 1961
	Troops working and sleeping in unheated tents in Arctic for 16 days at –30 to –20 °C	Radomski et al. 1982
Artificial acclimatization to cold air	1 week at –29 °C in climatic chamber	Horvath et al. 1947
	Subjects wearing shorts during day and sleeping under woolen blanket for 2 weeks at 15.5 °C	Iampietro et al. 1957
	Exposure of subjects wearing shorts for 8 hr/day over 31 days at 11.8 °C	Davis 1961
	Subjects spending 7.5 hr/day for 19 days at 6 °C	Keatinge 1961
	Clothed subjects for 8 hr/day for 5 weeks at 5 °C	Joy 1963
	Subjects in shorts at 5 °C for 4 hr/day, 5 times per week for 6 weeks	Newman 1968
Artificial acclimatization in cold water	1 hr/day immersion for 8 weeks at 32 to 21 °C	Lapp and Gee 1967
	Diving 1hr every day for 1 month in water at 0 to 3 °C wearing neoprene suit	Skreslett et al. 1968
	Daily immersion for 20-50 min 5 days/week for 2 weeks at 15 °C (French Baths)	Boutelier et al. 1974

Natural Acclimatization

Two groups of scientists examined seasonal changes in two different groups of subjects in two different climates (Leblanc, 1956; Davis & Johnston, 1961) to assess whether chronic exposure of humans to cold for months will induce the type of cold acclimatization observed in the chronically adapted rats and in native populations. LeBlanc followed a group of soldiers posted from Winnipeg to Fort Churchill at the end

of October where they lived outdoors for approximately 12 hr/day, 6 days a week, from the end of November until April. Their activity consisted of daily walks of 10 miles and standing motionless on guard duty for 2-3 hr at night. Their metabolic and thermal responses were measured at the end of November, December, and February.

In the Davis and Johnston study, subjects were examined once monthly from October to February. These were laboratory personnel who normally worked 40 hr/week in air-conditioned facilities and in heated quarters in the winter. Their combined data are re-plotted in Figure 11.Although the studies of Davis and Johnston and Leblanc described above did involve individuals exposed to intermittent cold, such individuals were well protected by clothing and their type of exposure would not be typical of one of intermittent repeated exposures to extreme cold. It is evident from these two different experiments in two different climates with different daily periods of exposure to cold that cold-induced heat production decreased significantly from Oct to Mar, and that the % shivering decreased to low levels by Feb. Body temperature data did not show any significant trends.

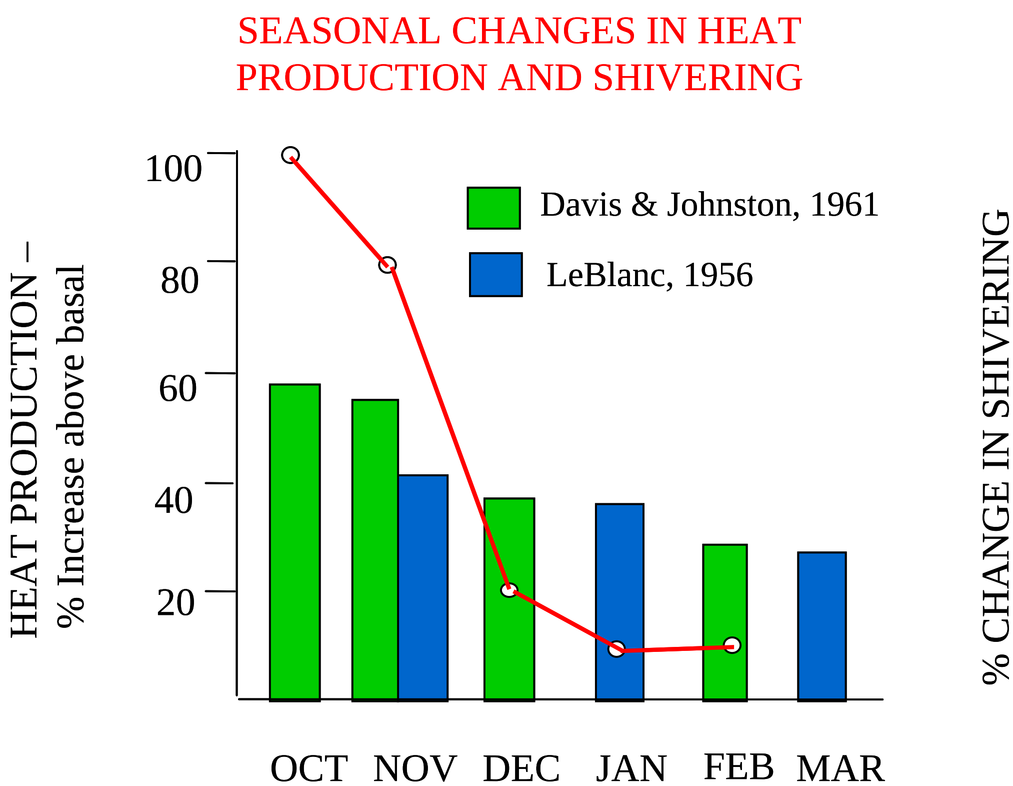

Figure 11. Seasonal changes in heat production in two groups of subjects from October to March. The Davis group was located in Kentucky and mean monthly temperatures varied from 13 to –4 °C from Oct to Feb. The Leblanc group were located in Fort Churchill in the Canadian sub-arctic with seasonal temperatures varying from –11 to –30 °C. The solid bars represent heat production as a % change from basal levels and the solid line represents the % shivering in the Davis group.

Davis and Johnston (1961) pointed out that the decrease in heat production was much less than the decrease in shivering and suggested that this might be due to a compensatory increase in non-shivering thermogenisis to replace shivering heat production. On the other hand, this data could also be interpreted as the development of Insulative Acclimatization, rather than an increase in non-shivering thermogenesis. However, such a process of acclimatization has little military value because of the long period of time required to induce some form of acclimatization.

Artificial Acclimatization

Humans are generally much more exposed to intermittent severe cold (IS) than to continuous cold (CM) and various groups have shown the development of a type of IS adaptation in humans. There are two basic techniques for rapidly inducing whole body IS-adaptation in humans:

- : short daily immersions of nude humans in cold water *(french baths)* ((Boutelier et al. 1974); and
- repeated nude exposures to cold air (Bruck et al. 1976).

However, the practical value of such techniques to military personnel subsequently going into the Arctic for a period of time had not been assessed.

Operation Kool Stool

In order to address this deficiency, Operation Kool Stool, a joint military experimental trial between our centre in Toronto, DCIEM, and the French air force and army medical laboratories, LAMASS and CRSSA, was carried out to assess the feasibility, practicality, and value of applying the "*french bath*" technique to rapid pre-adaptation of troops being airlifted into an Arctic environment. This was a joint military group composed of Canadian army subjects with no prior preadaptation to the cold (NPA) and a group of French soldiers who were preadapted to cold-water immersion (PA). Prior to embarking for Toronto, the French troops were subjected to the Boutelier IS technique of a total of nine daily immersions in water at 15°C for 25 to 40 minutes until their rectal temperature had reached an end-point of 35 °C (Figure 12). Immersion times gradually increased from 25 minutes to 40 minutes by the end of the last immersion indicating an increasing tolerance to cold with each repeated immersion.

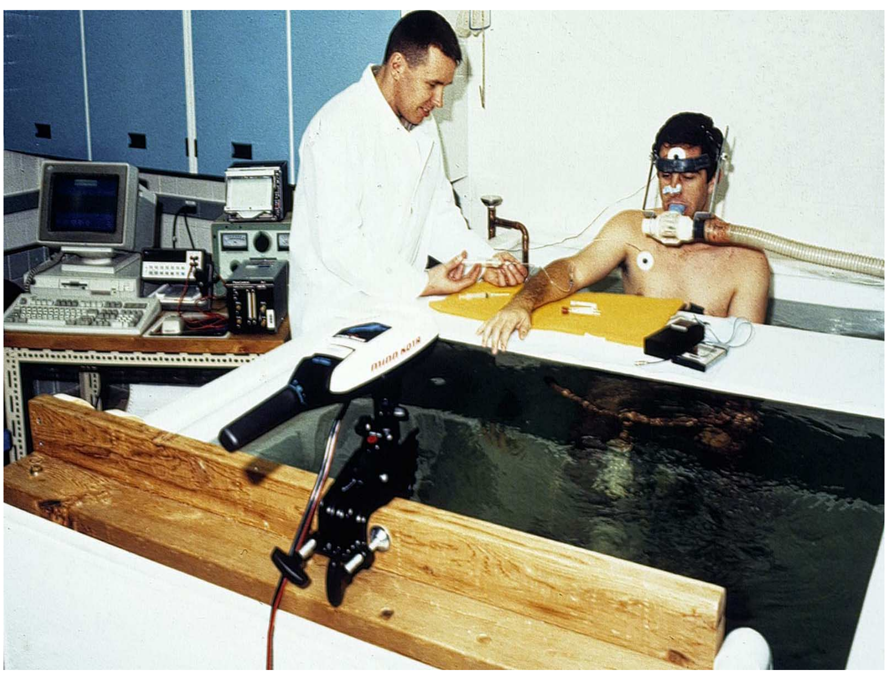

Figure 12. French bath immersion technique in cold water This consisted of 9 immersions in water at 15°C for 25-40 minutes.

The French troops arrived in Toronto 15 days after the last immersion and along with Canadian troops who had not undergone IS adaptation, were subjected to a standard nude cold tolerance test (NEC1) which consisted of lying semi-nude on a cot at 10°C for 60 minutes. Five days later, the troops were flown to Fort Churchill where they spent 16 days and nights performing 6 hr of light outdoor activity daily and sleeping in standard Canadian Forces sleeping bags in unheated tents. Over the period of the trial, the mean nightly temperatures varied between –25°C and –30°C, with one warm night of –10°C half way through the trial.

While in the Arctic, sleep polysomnography, diuresis, catecholamine and 17-OHCS excretion, and thermal and psychosociological responses were continuously monitored. Subjects experienced the greatest cold discomfort and its effects on diuresis and sleep while in their sleeping bags during the night. At the end of the 16-day trial, the troops were flown back to Toronto and subjected to a second nude cold tolerance test (NEC2). Some of the changes observed in the parameters are shown in subsequent figures. The complete study has been published in a Franco-Canadian Accord Volume (Radomski et al.. 1982) and certain chapters in the open literature.

Figure 13 shows the metabolic responses of the non-preadapted (NPA) and the preadapted (PA) groups to the nude cold tolerance tests before (NEC1) departing for the Arctic, and after 16 days in the Arctic (NEC2). A significant difference between the two groups prior to departure for the Arctic (NEC 1) was seen. Whereas the NPA group exhibited the normal increase in metabolism upon exposure to cold, the PA group did not increase their metabolic rate until after 50 min. After 16 days in the Arctic, the NPA group showed a similar response to the PA group to a NEC 2, in that no significant increase in metabolism occurred over the 60 min of cold.

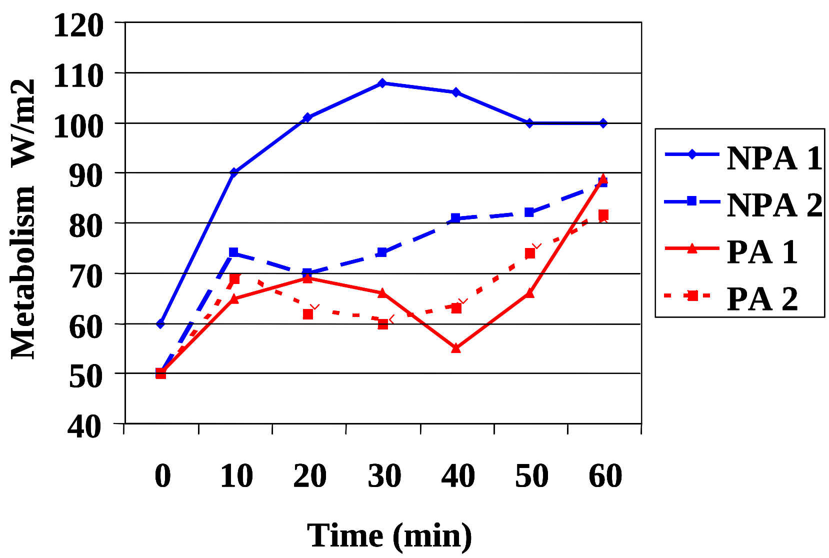

Figure 13. Metabolic responses of the non-preadapted (NPA) and the preadapted (PA) groups to the nude cold exposure tolerance test before and after 16 days in the Arctic.

Comparing the MR to the mean body temperature (Figure 14) revealed a similar metabolic response in the NPA group as observed by Hammel in his early experiments with control subjects (Figure 3) whereas the response of the PA group was more reflective of the Kalahari Bushman in that metabolism showed little increase (an insulative adaptation!). After 16 days in the Arctic, no differences in the MR vs Tb relationship were seen in the PA group, but it appeared that the NPA group had altered its response with a smaller increase in MR with a drop in Tb suggesting that the NPA group was developing more of an insulative

adaptation rather than a metabolic adaptation. Prior to departing for the Arctic, there were no differences in the response of the extremities to cold-water immersion (cold-induced vasodilatation response – CIVD) whereas after 16 days in the Arctic, a significantly improved adaptation of the extremities had developed in all of the subjects resulting in warmer extremities (Figure 15).

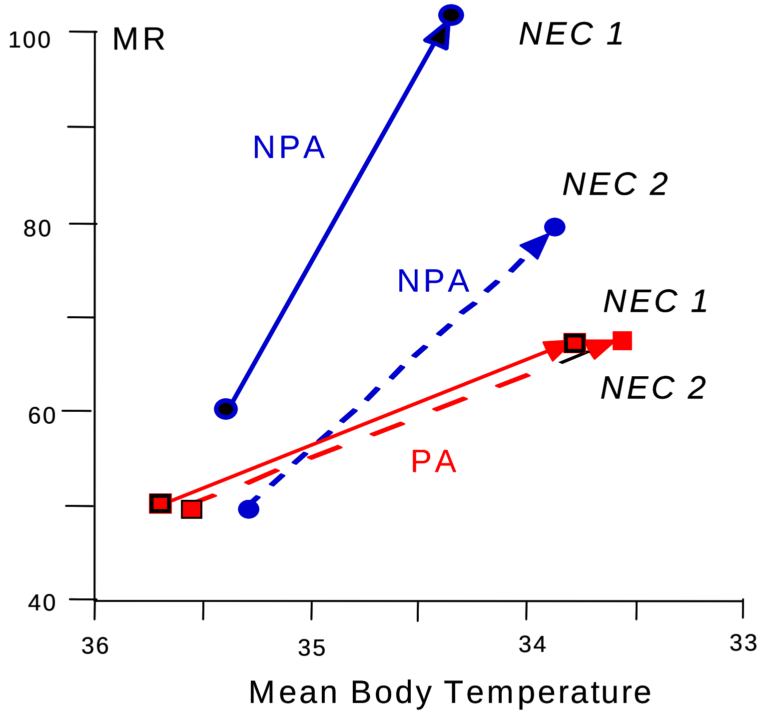

Figure 14. Change in the metabolic rate (MR) as a function of mean body temperature. A significant difference existed between the NPA and PA groups prior to the Arctic sojourn (NEC 1) and after 16 days in the Arctic (NEC 2).

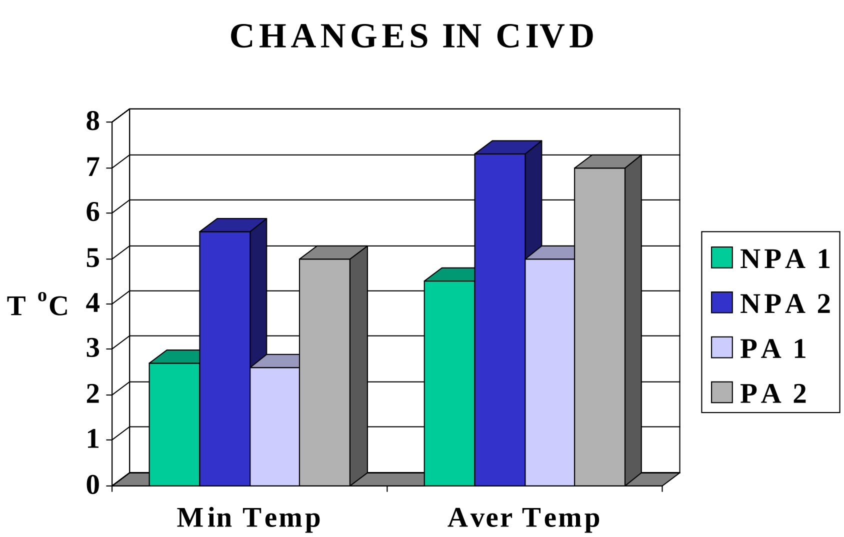

Figure 15. Changes in the Cold Induced Vasodilation response before and after 16 days in the Arctic. Min Temp is the lowest temperature to which the fingers dropped, and Aver Temp is the average temperature over the period of immersion of the finger in ice water.

Cold diuresis is a well-known condition in humans exposed to cold and this was evident in our NPA group during the night with significantly increased urine output (Figure 16). Cold diuresis also interferes with sleep as subjects find themselves getting out of their sleeping bags to urinate, thus increasing their cold exposure during the night. However, we were surprised to find that the PA subjects showed no cold-induced diuresis during their sojourn in the Arctic suggesting that the normal decrease in ADH found in the cold was prevented by prior cold adaptation. The 17-OHCS response was similar to the diuresis response, with the NPA group showing increased excretion of 17-OHCS during the night, reflective of a stress response, whereas the PA group showed no such stress response.

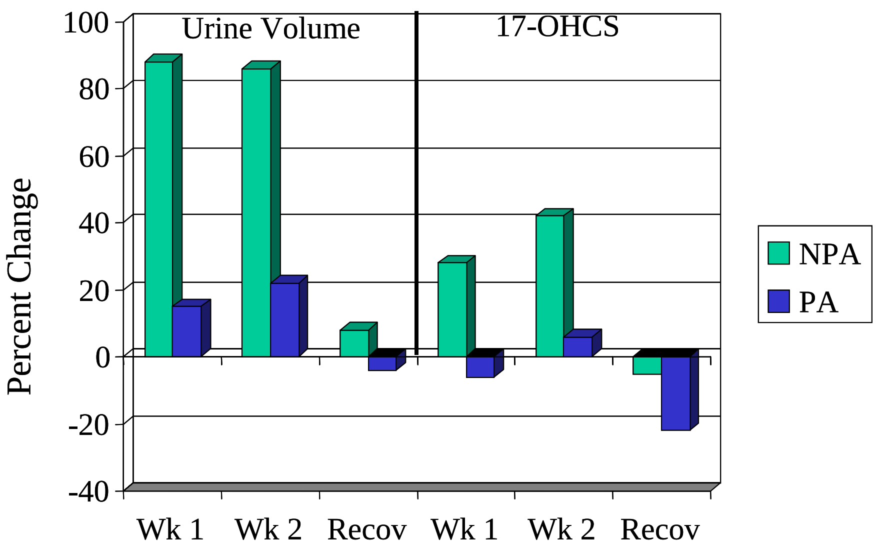

Figure 16. Cold-induced diuresis and 17-OHCS excretion in NPA and PA subjects in the Arctic. The values are expressed as percent change from normal.

We also found significant differences in hormonal responses between the two groups in the Arctic (Figures 17). Although the NPA group showed the expected increase in noradrenaline as has been observed by others, no such increases occurred in the PA-group, a characteristic of IS-adapted animals. It is known that IS adaptation of animals results in no changes in noradrenaline excretion or sensitivity to noradrenaline. This is in keeping with a hypothermic insulative type of adaptation.

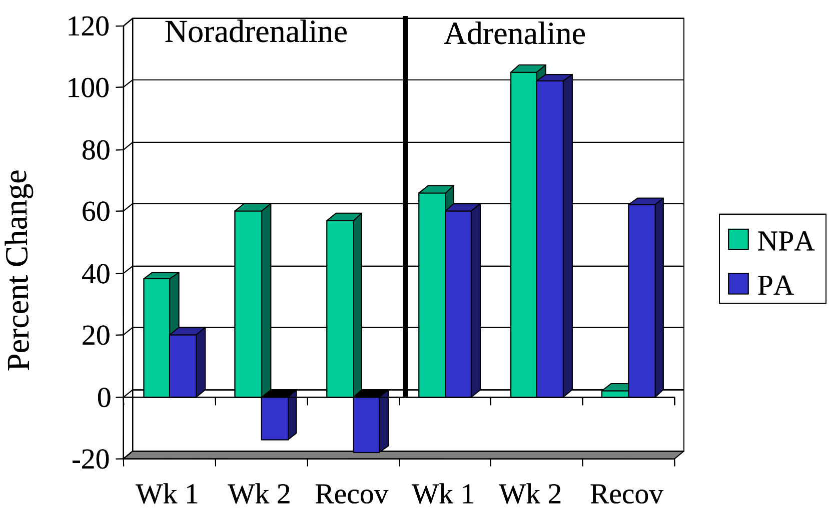

Figure 17 .Percent change in norepinephrine and epinephrine excretion in the NPA and PA groups in weeks 1 and 2 in the Arctic and during recovery in a temperate environment.

We were only able to do polysomnography on the NPA subjects. However, insomnia did occur as a result of the cold stress at night, mainly in the second half of the night (Figure 18). This was accompanied by intense shivering and awakenings.

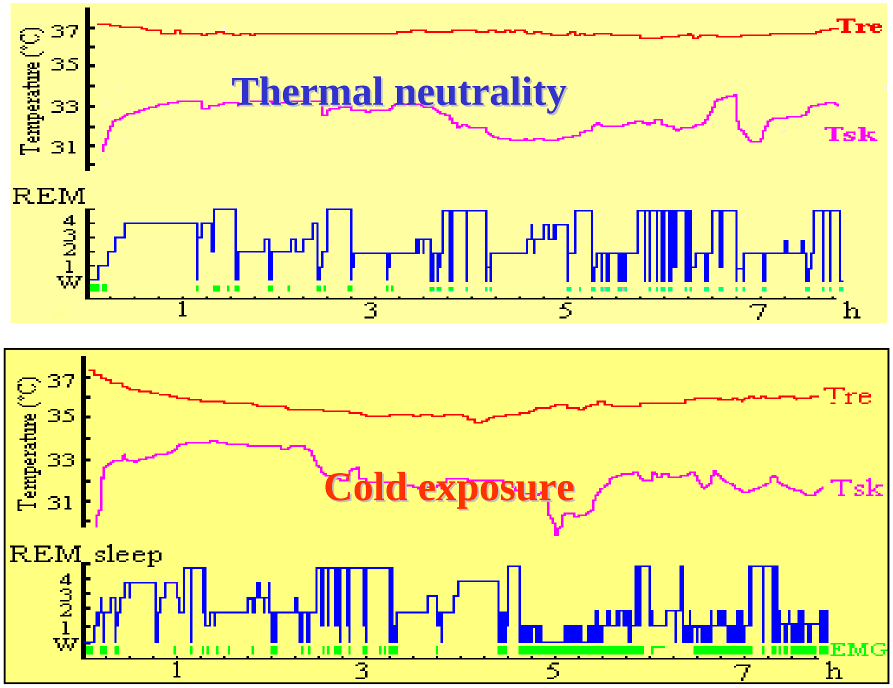

Figure 18. Rectal temperatures and hypnograms during sleep under thermal neutral conditions and during sleep in the tent in the Arctic.

The major sleep change was a chronic depression in paradoxical sleep, which appeared to be inversely correlated with 17-OHCS excretion and environmental temperature (Figure 19). As the excretion of 17-OHCS increased with a decreasing environmental temperature, the amount of PS deprivation increased. Other stresses have been found to produce similar effects.

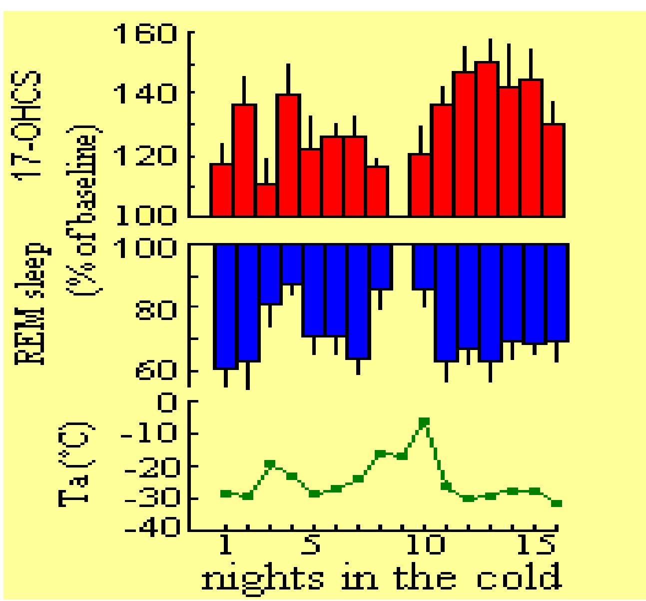

Figure 19. Variation in paradoxical sleep, environmental temperature, and 17-OHCS excretion.

Kool Stool Conclusions

In conclusion, it appears that IS technique using cold water immersions is (Figure 20):

- a rapid technique for inducing cold adaptation
- eliminates cold diuresis and therefore allows undisturbed sleep,
- persists over a significant period of time of the order of a month,
- results in a shift of the shivering threshold to a lower body temperature,
- requires a shorter period of time to induce and is a simple technique,
- similar to the hypothermic insulative responses shown by the Aborigines and the Bushmen.

In terms of military practical value, the IS technique would appear to be the method of choice for rapidly increasing cold tolerance in troops, such as special forces that might be airlifted at short notice into extreme thermal climates.

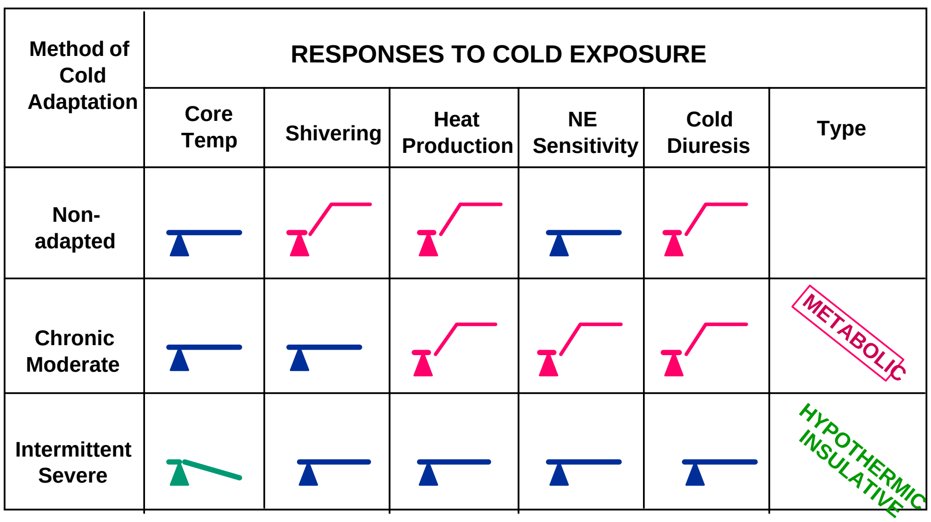

Figure 20. Summary of responses of non-adapted and cold-adapted humans and laboratory animals on subsequent exposure to cold (adapted from LeBlanc 1978).

This paper has attempted to review some of the classical studies of how different human populations have adapted to the cold with a minimum of resources and how one could induce an adaptation similar to these groups in a relatively short period of time. The rest of this Symposium will address the current advances in protecting man from cold and hot environments through technology, but technology does break down, and perhaps a combined approach of protection and rapid adaptation will prove more beneficial rather than solely relying upon technology

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Recent Advances in Protective Clothing Technology

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SUMMARY

Several recent advances in protective clothing technology are presented. The advances are related to floatation, thermal protection, anti-gravity protection, and the integration of protective clothing and equipment, which are specific areas of technical expertise for Mustang Survival Corporation.

INTRODUCTION

Mustang Survival [1] is a privately owned Canadian corporation founded in 1967 by Irving Davies. Mustang Survival's early success was related to the design and manufacture of *flotation* and *hypothermia* protective clothing. Over the last decade, the corporation has expanded into the areas of *active cooling*, *anti-gravity* protection, and the *integration* of protective clothing and equipment.

Mustang Survival is rather unique in the clothing industry, in that, it has research and development (R&D) capabilities. In addition to assisting the corporation' industrial, recreational, and military product lines, R&D is contracted externally. This paper details some of the more recent advances in clothing technology made by Mustang Survival and provides their relative pros and cons.

TECHNOLOGIES

Flotation

Life Preserver/Survival Vest (LP/SV)

The Life Preserver / Survival Vest (Mustang MSV 971 LP/SV series) has been in use with the Canadian Forces (CF) since the early 1990's. There are several variants of LP/SV configuration in use with NATO aircrew. In general, the LP is an inflatable device that provides 35 to 37 lbs (156 – 166 N) of buoyancy. The bladder is shaped like a conventional "horse-collar" design. The SV has many different pocket configurations.

Generally, the LP/SV is capable of consistently *self-righting* most aircrew unless it is worn in conjunction with immersion suits and/or anti-G garments, which trap large amounts of air or are inherently buoyant. *Self-righting* is the ability of a flotation device to turn an unconscious, immersed subject from a face down to a face up orientation. This potential safety concern exists with most aircrew immersion suit and LP/SV combinations. Recent advances we have made in flotation technology have attempted to address this particular performance issue.

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

NASA Life Preserver Unit (LPU)

In 1994, Mustang Survival developed the LPU used by NASA Space Shuttle Crewmembers (Figure 1). The LPU has been in-service with NASA since 1995. The shape of the current inflated LPU bladder is rather unconventional. It provides 129 lbs (576 N) of buoyancy, an unusually high amount.

The ability to *self-right* the crewmember was a key performance requirement of the NASA LPU design. The crewmember's inflated anti-G trouser can cause them to float horizontally on the surface of the water. This position can be very stable, whether on one's side, face up or face down. This makes inducing a moment of rotation around the lengthwise axis of the body, very difficult. It was also observed that the dangling backpack, which contains the crewmember's survival water ration, either aids or hinders self-righting. With the anti-G trouser deflated, self-righting is achieved. With the trouser deflated, the crewmembers' legs drop in the water and they no longer float in a stable horizontal position. The large volume of the front lobes, the overall shape of the inflated bladder, and method of anchoring to the body are keys to achieving self-righting.

The Shuttle crewmember's helmet has an anti-suffocation valve located near its base, which must remain above water. The current LPU has such a large inflated volume, in order to provide the unusually high amount of *freeboard* (defined as the distance between the water surface and lowest breathing cavity) required by Shuttle crewmembers. The LPU provides the wearer with improved field of vision, which seems to impart a feeling of being in greater control (Figure 2).

With such a large volume LPU, the crewmember's in-water *mobility* and ability to board a their single-person life raft becomes more difficult. Small stature crewmembers found boarding the raft in calm water with the inflated LPU to be either impossible or very difficult. In most cases, deflation of the LPU aided boarding. It was observed that the bladder bulk beneath and behind the crewmember's arms hindered the range of arm motion necessary to pull the nose of the partially inflated life raft underneath their posterior.

Figure 1 – Side view of current NASA LPU

Figure 2 – Front view of current NASA LPU

NASA Enhanced Life Preserver Unit (ELPU)

In 2001, Mustang Survival developed a prototype Enhanced Life Preserver Unit (ELPU) for NASA. The new ELPU design addressed the in-water mobility deficiency noted with the current in-service LPU when worn by small crewmembers.

Ultimately, the original LPU was re-shaped to improve mobility (Figure 3). This advance did not come easy! Numerous iterations of design and water testing were conducted. Initially we reduced the bulk of the bladder by a considerable amount, in order to try and improve arm mobility. But when we reduced bladder bulk beneath the arms, we lost critical freeboard and self-righting became less consistent. As we recovered flotation performance by increasing buoyancy in several key areas, we restricted mobility again! During testing with various subjects, each with their own custom-fit parachute harness, we noted performance differences attributable to variability of the LPU-to-body anchoring points.

A multitude of different bladder shapes was tested. The final solution involved "scalloping" or carving out regions of the bladder directly beneath and behind the wearer's arms (Figure 4). The ELPU design is about to undergo extensive evaluation and hence is not presently in-service with Shuttle crewmembers.

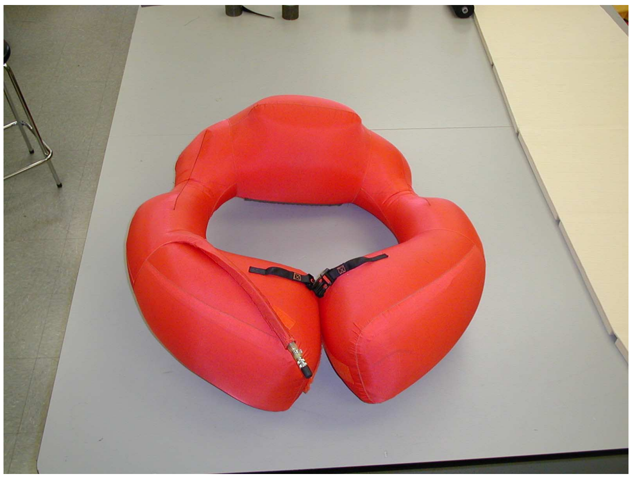

Figure 3 – Front view of prototype NASA ELPU

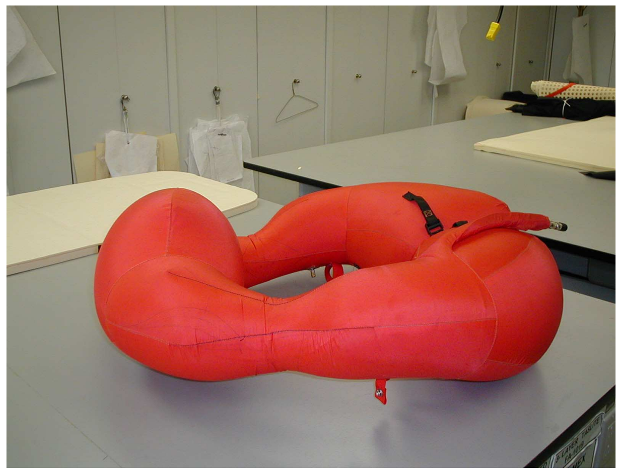

Figure 4 – Side view of prototype NASA ELPU

Advanced Life Preservers

The basic shape of the in-service NASA LPU design spawned several variants of inflatable LPUs that are now commercially available. Each LPU has subtle differences that make it perform with particular immersion suits. These variants are now worn by helicopter passengers transiting to and from oil/gas platforms offshore of Canada and the United States. The Canadian Forces have also investigated the performance of this helicopter LPU with several constant-wear aircrew anti-exposure coveralls.

Beware. The performance of any type of flotation device is very dependent on the immersion suit it is worn in conjunction with. *Self-righting* is not necessarily achieved with any subject, in any water condition and any form of immersion suit with such an LPU design. Secure anchoring of LPU to body and/or suit is one of the keys to achieving self-righting performance.

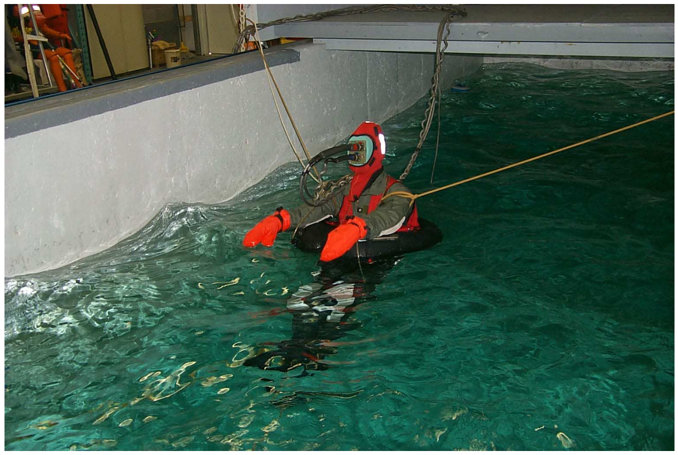

Figure 5 – Thermal manikin evaluation of MAC200 and advanced life preserver

The physical interactions between the human, suit, flotation device and environment are complex and even with the present body of knowledge in this subject area, it is extremely difficult, if not impossible, to understand these interactions via dynamic hydrostatic computer modeling. Mustang Survival is continually exploring many advanced life preserver concepts aimed at providing high freeboard, stability, ample field of vision, and self-righting with immersion suits. There are likely potential benefits in terms of hypothermia protection that may be achieved by removing the torso from the water (Figure 5). This really should be investigated further.

Wind Blast - Life Preserver / Survival Vest

Mustang recently improved its LP/SV that is in use with the Canadian Forces. The advance addressed a deficiency noted during ejection testing at 600 knots. At this speed, items of survival equipment were at risk of being lost from the vest pockets. The LP bladder and cover were at risk of being stripped from their attachment points on the SV carrier. Displacement of the beaded LP inflation lanyard may also inadvertently inflate the LP.

Flaps and closure methods on the SV pockets were re-designed to prevent their loss of contents upon ejection. A protective cup and snap system was designed to stop the flow of forced air from entering the LP securing strap points at the base of the LP cover. An elasticized cover was added to protect the automatic inflation lanyard. The design changes to the LP/SV have been verified in actual ejection testing. The LP/SV is capable of integrating with an air-cooling vest and ballistic panel inserts meeting NIJ Level III.

Damage Tolerant Inflatable Personal Flotation Device

Another recent advance in personal flotation is our Damage Tolerant Inflatable PFD [2]. Due to multiple self-shifting bladders, this PFD can sustain limited puncture damage from snags, bullets and shrapnel yet remain inflated. Comprehensive ballistic testing of the PFD and its compressed gas inflation system is currently being conducted in conjunction with Pacific Body Armor of Kelowna, British Columbia, Canada and several other agencies.

Re-breather Hood

Two key factors in one's ability to egress from a water-ditched aircraft or submerged vessel are the ability to breathe and see [3]. In an attempt to address these, we designed a waterproof hood [4] that could be donned by simply pulling it overtop of one's head while in air. The hood is watertight and seals around the wearer's

neck. Air trapped within voids inside the hood is re-breathed for a limited duration. The hood has a flexible, transparent visor that assists vision by allowing the wearer to open their eyes and focus underwater.

Testing was conducted to determine gas exchange through the gas permeable hood while wearing the hood in air and to determine average underwater breathing times. The prototype hood is sitting on the shelf, awaiting some form of user interest.

Stretcher Evacuation

A system similar to the re-breather hood was designed for protecting the whole body. The prototype system was intended for evacuating stretcher-bound medevac patients from inside a water-ditched or submerged vessel. The system encloses the entire stretcher in a waterproof sack thus providing both short-term breathing and vision underwater as well as thermal protection and flotation at the water surface. Several waterproof zippers were provided for accessing the patient.

The waterproof sack had exhaust valves and the stretcher was equipped with three inflatable bladders. This combination allowed stretcher egress assistant(s) to vent air from the sack for the low buoyancy needed for underwater egress and to establish high buoyancy which brings them to the water surface in a stable floating position. The prototype system was also capable of self-righting. Once at the surface, the visor region could be unzipped to open the system for long-term breathing and patient access. In 1994, underwater egress of a stretcher-bound subject was demonstrated at Survival Systems Limited by the CORD Group of Dartmouth, Nova Scotia, Canada. The prototype has not received any interest since.

Thermal Protection

Mustang Survival has been experimenting with various approaches to providing thermal protection during immersion in cold water, particularly for users who need constant wear protection yet may be working hard and/or exposed to hot environments.

For the designer, providing protection against both environmental extremes with passive insulation is a daunting challenge, wrought with compromise. Typically, a minimum insulation level of 0.75 immersed clo is required for aircrew. This results in clothing with insulation of between 1.6 to 2.0 clo in still air. This is essentially backwards to the ideal, in which, insulation levels in water exceed those during normal wear in air.

If one is to view the ratio between a garment's immersed insulation (I_{imm}) and insulation in still air (I_{air}), a potentially meaningful index related to overall thermal protection is formed (i.e. $i = I_{imm} / I_{air}$). For a nude subject in still air, thermal insulation is about 0.8 clo [5]. Nude in still water, thermal insulation can drop as low as 0.06 immersed clo [6]. This example would equate to an index of only 0.08 (i.e. 0.06 / 0.8), which would be indicative of poor overall thermal protection. Typical aircrew immersion suits provide about 2.0 clo in still air and 0.75 immersed clo, which gives a slightly higher index in the order of 0.38. If we could provide a minimum of 0.75 immersed clo and the same level of insulation in still air, the index would near 1.0. The ideal, which would occur when immersed insulation exceeds insulation in air, would have an index greater than 1.0. We have a long way to go if we want to achieve such an ideal ratio of thermal insulation!

Immersion Suits

One of our immersion suit designs has attempted to address the compromise that must be made to achieve such insulation levels. We've attempted to minimize thermal insulation during normal wear by making waterproof vapour permeable suit that is more tolerant in terms of losing thermal insulation should highly probable suit leakage occur during immersion. Most in-service dry suits are known to be prone to leakage. On average, they lose forty percent of their insulation with one litre of leakage [7].

The design decision was made to allow small amounts of leakage via cuffs at the neck and wrists. Accepting leakage allowed us to design adjustable cuffs that could be worn loosely open yet tighten when required. Since the cuffs are less constrictive than typical latex cuffs, they are more comfortable and their openness allows for dissipation of air, saturated with perspiration, from inside the suit.

An unconventional zipper configuration was chosen as an alternate way to provide both donning/doffing and the ability to relief oneself via a single waterproof zipper. There is an aircrew (MAC200) and a marine variant (MSD900) of the suit available. Both suits are currently seeing extensive evaluation by numerous government agencies. On the aircrew version, the zipper forms a helix around the torso [8]. To-date the basic suit design has met with both user acceptance and dislike. In particular, the zipper and cuff configuration have met resistance with certain users; more "user-friendly" zipper designs have been developed.

In terms of immersion protection, thermal manikin testing indicates that this suit design can achieve 0.91 immersed clo in stirred water and 1.63 clo in air. This equates to an immersion protective index of 0.56 (i.e. 0.91/1.63).

Atmospheric Self-Inflating Immersion Suit

A higher level of insulation in the order of 1.0+ immersed clo is typically achieved by neoprene foam immersion suits and life rafts. Both approaches occupy a large storage volume and are not generally considered as portable or wearable.

In 1993, Mustang Survival developed a low volume, high insulation immersion suit [9]. We created a 1.0 immersed clo immersion suit that uses a compressible insulating medium packaged in waterproof bladders. Use of a compressible medium, allows one to significantly reduce suit volume via vacuum packaging. The prototype suit is configured into a wearable "fanny" package with a total volume and weight of 5.5 litres and 2.4 kg, respectively. Since the insulation is resilient it forces the suit to self-inflate automatically upon opening of the vacuum package, in a manner similar to military self-inflating sleeping mattresses. The suit is multi-segmented to minimize water absorption in case of damage. Although, the suit has not seen operational use, an inflatable mitt and hood based on this concept have.

Thermal Undergarments

Thermal undergarments or dry suit liners have also seen recent advancements. One variant is that of water vapour permeable foam [10,11,12]. Its advantage over traditional fibrous battings and fleece is that it is inherent buoyant, non-absorbing, and resists hydrostatic compression. This does result in a somewhat heavier and stiffer undergarment though.

We also developed an incompressible diver's undergarment that resists hydrostatic compression experienced in diving operatons. It uses a fibrous batting that is pre-compressed during undergarment manufacture, to reduce any subsequent loss of thickness due to hydrostatic compression it sees in use. The undergarment includes a layer of waterproof, vapour permeable fabric to prevent external suit leakage and condensed perspiration from penetrating the insulating fibers. Both these features help it retain its in-water insulation.

Undergarments, which are inflatable upon immersion, have also been investigated. While variable insulation undergarments may offer slight improvement to thermal comfort and protection, it will improve to the degree ultimately required. Passive forms of insulation will only take us so far towards our thermal protection goal.

Active Heating

In 1995, Mustang integrated fabric laminates containing anhydrous magnesium chloride into anti-exposure coveralls (MS-195), as a means of actively heating water that is trapped inside the garment during immersion in cold water. Upon immersion, water-activated valves opened allow liquid water a pathway to the inside of the fabric laminate. The liquid water was prevented from making direct contact with the thermo-chemical by the presence of a series of waterproof, water vapour permeable membranes. These membranes allowed water vapour to diffuse into the thermo-chemical and deliquese at a controlled rate. This approach prevented dangerous over-heating due to thermal runaway and retained chemical reactants and products to prevent contact with skin or eyes. The entire laminate was sealed in polyurethane-coated nylon, to prevent both liquid water and its vapour from sources such as high humidity, sweating, condensation, spray, and rain etc., from activating the thermo-chemical.

Testing on a thermal manikin demonstrated an increase in the suit's immersed thermal insulation due to active heating, whereas, limited testing on humans showed an insignificant thermal benefit. It was determined that heating the water trapped within this particular garment microenvironment reduced shivering intensity and hence the amount of metabolic heat production. We have not investigated thermo-chemical heating since.

Enhanced Personal Cooling

At present, if we provide the level of immersed insulation needed, active cooling is required during constant wear. Mustang Survival recently developed a prototype Enhanced Personal Cooling Garment (EC) which uses a different approach than existing AC or LC [13,14]. The garment contains a thin layer of water and is worn next to the skin. Evaporation of water from the bladder extracts heat from the skin and underclothing.

When worn beneath air-cooling vests, cooling is enhanced as airflow increases the rate of evaporation hence the rate of cooling. EC also has a passive cooling potential without airflow. Human testing of the enhanced personal cooling garment is discussed in Paper #17.

Integration

Smart Aircrew Integrated Life Support System (SAILSS)

The F-22 air-cooling vest (Figure 6) made by Mustang Survival is currently being investigated as a platform for SAILSS physiological sensors. The intent is to first integrate Mustang Survival's Enhanced Personal Cooling Garment technology with current air-cooling vests in conjunction with Titan System's Semcor Division. Conceptual approaches to integrating cooling, SAILSS and the Navy Combat Edge CSU-21/P counter pressure vest are also being considered at the present time.

Tactile Situation Awareness System (TSAS)

The F-22 air-cooling vest is also being used as the platform for attaching Tactile Situation Awareness System (TSAS) tactile sensors ("tactors"). Tactors present information on orientation to pilots and aircrew via tactile sensory receptors [15].

The F-22 air-cooling vest was found to apply pressure, which increased tactor-body contact. Generally, the United States Naval Aerospace Medical Research Laboratory (NAMRL) found tactor-body contact to be troublesome throughout their evaluation programs. To address this deficiency, Mustang Survival was tasked by NAMRL to develop a prototype garment that provided a platform for the tactor array, air-cooling over the torso, and applied both low and high pressure against the tactors. Concave-shaped regions of the body, such as the lower back, spine and sternum, required three discrete high-pressure bladders to improve tactor-body contact.

Figure 6 – F-22 air-cooling vest (MSF843)

Anti-Gravity Protection

ATAGS - Magnetic Resonance Imaging

During development of the Advanced Tactical Anti-Gravity Suit (ATAGS), Mustang Survival applied magnetic resonance imaging (MRI) techniques to assess differences in the expansion envelope of inflated anti-G trouser bladders [16]. By wetting the trouser materials with water, the technique was able to image the garment and underlying tissues and bones. MRI proved to be a very effective tool for evaluating various design approaches that would limit ATAGS bladder expansion in regions previously causing cockpit interference.

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Physiological Assessments of Permeable NBC Protection Clothing for Hot Climate Conditions

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1 Introduction

Against the background of the increasingly less clearly calculable and thus still present NBC threat, NBC protection is of highest priority in all modern armies today. Therefore, individual NBC protection, including the ability to carry out actions under NBC conditions, is very important. Especially, the direct protection of the soldier against the effects of applied NBC and incendiary weapons on his sensitive organism calls for the consequent consideration of these aspects even under the mission conditions to be expected in the future.

As individual NBC protection does not only represent the sum of the parts of the personal NBC protection equipment of the soldier individual NBC protection must be regarded as a whole taking the present and future requirements into consideration, and must correspond to the potential danger.

As the NBC protection function can not be fulfilled by any other kind of soldier's equipment the clothing physiology of the personal NBC protection equipment (including breathing and body protection) should be so that the wearer does not consider it to be a hindering „foreign body" that disturbs his actions.

Reliable breathing protection is absolutely necessary for the survival and function of the Soldier System as the incorporation of toxins via the respiratory tract is very dangerous for the human organism.

As chemical warfare agents can enter the human body not only via the respiratory tract but also via the skin the complete body must be protected against the influence of warfare agents. Therefore, it must be noted that the soldier can absorb a lethal dose of chemical warfare agents to be expected in a combat within only two minutes via the unprotected skin of the head and hands alone.

In addition to fulfilling the protection requirements, an important function of a permeable NBC protective suit is to regulate the heat and moisture exchange of the wearer with the environment so that it does not lead to overheating (hyperthermia) or undercooling (hypothermia). On principle, operating situations can always be problematic when a high energy consumption must be compensated for with intense heat production, for example when wearing NBC protective clothing in hot and moist (sub-tropical) climatic zone. In such cases there is the danger that the thermal balance (heat formation in organism = heat emission to the surroundings) will be interfered with and at times resulting in extreme over-heating (heat stress).

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

The stress resulting from the environmental situation comes in addition to the stress stemming from the wearing of the personal NBC protective equipment (NBC protective clothing, NBC respirator with filter canister, NBC overboots and NBC protective gloves), the enormous physical strain of the mission and additionally the weight of the equipment that the soldier must carry.

The task of equipping NBC protective clothing with good clothing physiological wearer characteristics has only been inadequately carried out up to now. That this point just as important is as the actual protective characteristics of the clothing is demonstrated by the experiences and discoveries during the Gulf War. Additionally, the increase in the requirement of the UN and NATO peace missions and the formation of crisis reaction troops has led to a further development in NBC protective clothing.

NBC protective clothing, which is lightweight and keeps the physiological stress of the wearer to the minimum, is being increasingly required. To keep the stress which results from wearing NBC protective clothing to a minimum, NBC protective clothing must be optimally designed regarding the clothing physiological aspect.

2 Structure and Functional Mechanism of an NBC Protective Clothing System

An NBC protective clothing system mainly consists of a multi-layer textile air-permeable surface compound with a shell fabric and a filter laminate each of which has a special function *[Figure 1]*.

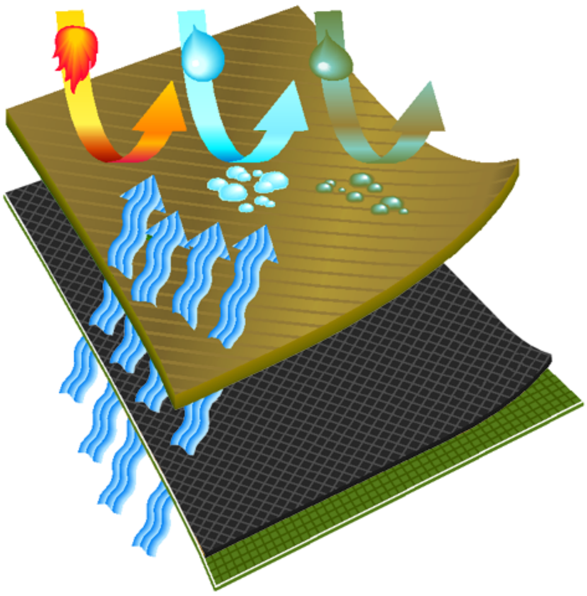

Figure 1: Structure of an air-permeable NBC protective clothing system

The strong barrier effect of the shell fabric (outer layer) prevents the penetration of radioactive particles or pathogenes passing through the textile surface compound. In addition, the oil and water repellent impregnation of the shell fabric prevents the absorption of liquid chemical warfare agents. The flame-retardant quality of the shell fabric as well as the thermal absorption capacity of the activated carbon, especially when being distributed homgeneously on the surface (this is e.g. very well developed in activated carbon fabric), provides protection against thermal effects. Specific requirements of missions at sea, e.g. resistance to water penetration, can be met by the integration of suitable permeable or semi-permeable membranes in the textile surface compound.

The filter laminate (inner layer with integrated activated carbon adsorber component) consists of a multi-layer compound structure in which an adsorber material (either activated carbon impregnated PU-foams, activated carbon spheres,, textile activated carbon adsorber, etc.) is embedded thus protecting the wearer of the suit against aerosol and gaseous chemical warfare agents by adsorption by the specific active surface.

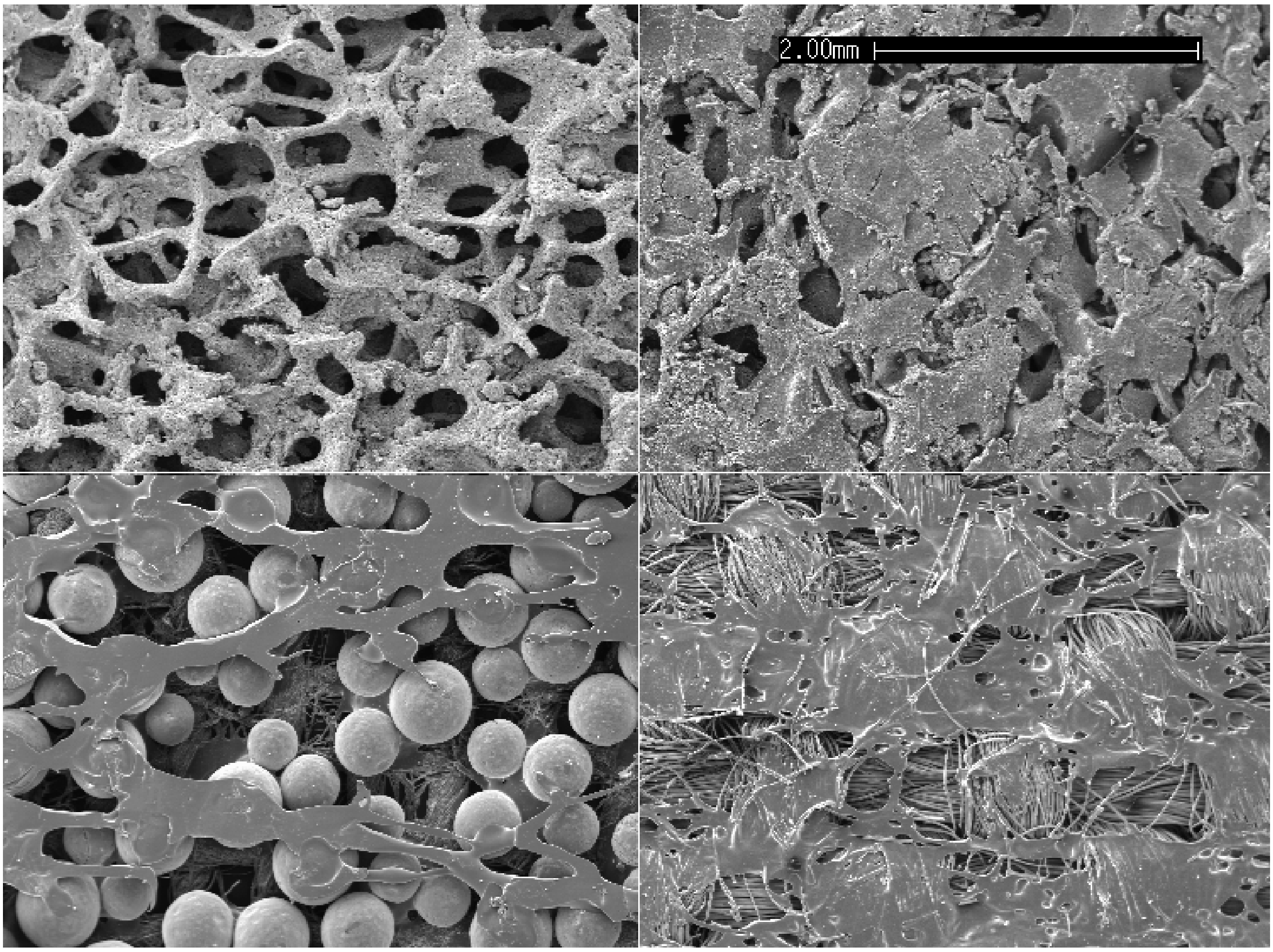

Figure 2: REM photographs of activated carbon adsorber materials:

Top left: Activated carbon impregnated PU foam (open cell)
Top right: Activated carbon impregnated PU foam (compressed)
Below left: Activated carbon spheres (covered by PU net)
Below right: Activated carbon fabric (covered by PU net)

The extremely high requirements of such an NBC protective clothing system are summarised in table 1.

Table 1: Requirements of an air-permeable NBC protective clothing system

- **Clothing physiological wearer comfort**
  - lightweight
  - optimal heat and moisture transport capability
  - controlled air-permeable textile layers
  - convenient design for good freedom of movement
  - no skin irritations
- **Protection against convective and/or radiation heat as well as direct influence of incendiary weapons (Napalm, etc.)**
  - flame-retardant properties
  - strong thermal absorption properties of the activated carbon component
- **Protection against mechanical influences**
  - high durability (tensile and tear resistance)
- **Resistance against POL's**
  - oil-repellent properties
- **Protection against specific chemical warfare agents**
  - multi-layer system structure with integrated activated carbon layer
- **Protection against contact with radioactive fallout or biological warfare agents**
  - multi-layer system structure and respective material thickness
- **Infrared reflectance**
  - IR remission of the shell fabric
- **Easy care**
  - washing at minimum 40 °C
  - dirt-repellent properties
- **Reuseability**
  - decontaminability
- **Compatibility**
  - with the other equipment components of the soldier
- **Easy and reliable handling**
  - also under stress

3 Clothing Physiological Wearer Comfort of NBC Protective Clothing

Situations in missions can always be problematic for the wearer of NBC protective clothing when his body is stressed and thus a high energy conversion (metabolic rate) has to be balanced by intensive heat production. This happens especially to wearers of NBC protective clothing in hot or muggy (sub-tropical) climatic zones. In these cases there is a danger of a disturbance of the thermophysiological balance (heat production in the organism = heat emission to the environment) and creation of a state of temporary extreme over-heating of the body (heat stress).

In addition to the stress resulting from the climatic conditions of the environment, there are other kinds of stress caused by the wearing of personal NBC protective equipment (NBC protective clothing, NBC protective mask with filter, NBC overboots and NBC protective gloves), the enormous physical stress arising from the action itself, and the weight of the other equipment the soldier has to carry. To keep the stress resulting from wearing the NBC protective clothing as low as possible the NBC protective clothing must ensure optimal clothing-physiological wearer comfort. For this reason, there is an increased demand for light NBC protective clothing systems which are less stressing with regard to clothing physiology.

In a critical evaluation, these principal requirements can not be fulfilled by an "NBC overgarment", i.e. an NBC protective clothing which is to be worn over the combat suit *[Figure 2 and 3]*.

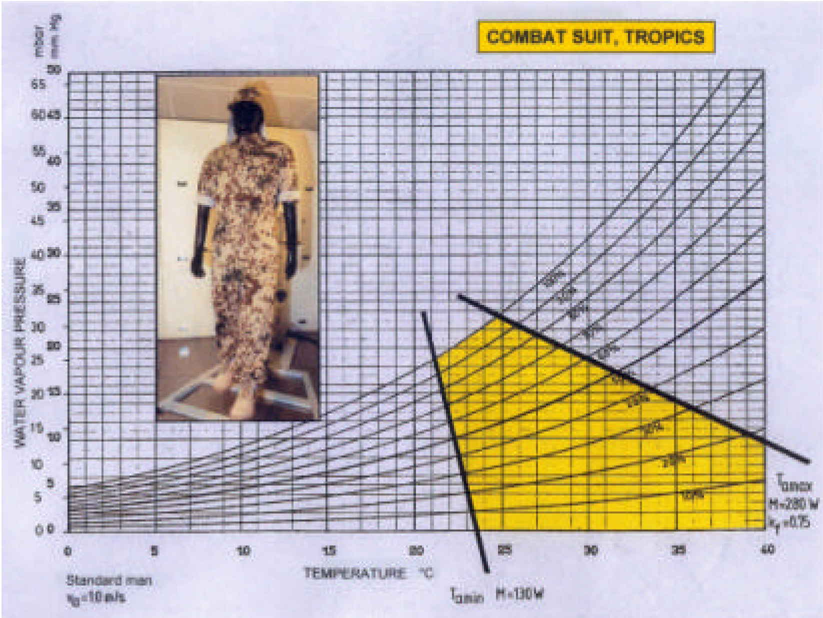

Figure 2: Wearer-physiological application area of a combat suit (yellow area)
(Source: Hohenstein Research Institute)

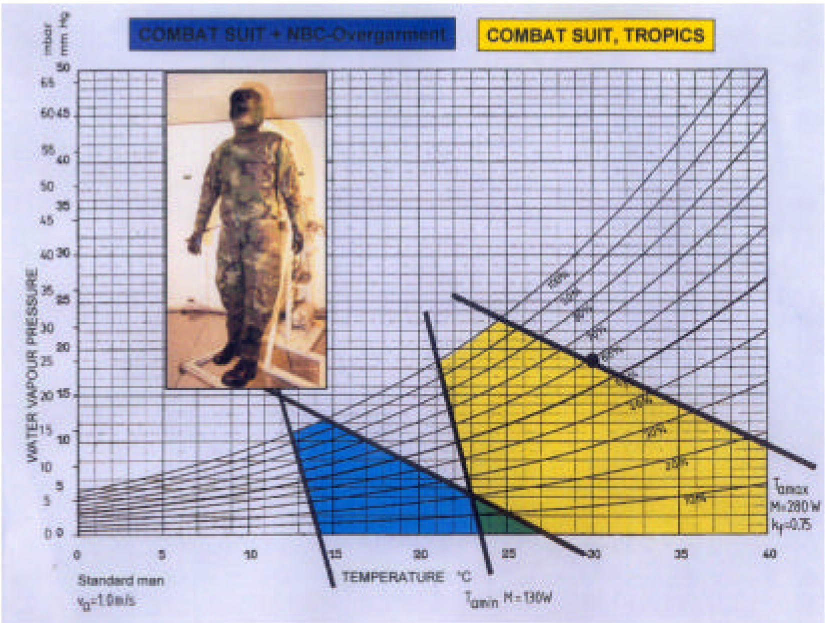

Figure 3: Wearer-physiological application area of an "NBC Overgarment" to be worn over a combat suit (blue area)
(Source: Hohenstein Research Institute)

3.1 Aspects, Components and Specific Parameters of the Wearer Comfort

The clothing-physiological wearer comfort mainly results from the following three factors:

- Thermophysiological wearer comfort
- Skin-sensoric wearer comfort
- Ergonomic wearer comfort

Clothing fulfills its wearing function and can be called "comfortable" *[Table 2]* if it has an optimal heat and moisture transport capability and a buffer effect, prevents unconvenient sensations when coming into contact with the skin, and does not hinder the freedom of movement of the wearer.

Table 2: Aspects, components and specific parameters of the wearer comfort

Aspect	**Components**	**Specific parameters**
Thermophysiological wearer comfort	Ensuring an even heat balance Avoiding the sensations "too hot" or "too cold"	Water-vapour resistance Heat insulation Moisture transfer index Air permeability Moisture compensation index Water-vapour absorption capacity Moisture compensation index Sweat transport Drying time Capillary transport
Skin-sensoric wearer comfort	Avoiding unconvenient sensations when coming into contact with the skin (no irritations such as scratching, itching, adhering to sweaty skin)	Adhesion index, surface index and moistening index Number of contact points between textile material and skin Stiffness
Ergonomic wearer comfort	Avoiding unconvenient heaviness and uncomfortableness Ensuring freedom of movement Optimal fit to the body Design	Fit Weight

4 Test Objectives

In the test carried out at Hohenstein Research Institute, two NBC protective clothing sets (Clothing system 1 and 2) *[Tables 3 and 4]* were tested for their usability in hot climatic zones with regard to clothing physiology *[9]*. The test objectives were:

- Measuring the thermal and water-vapour resistance of the individual textile layers of the clothing systems using the thermoregulatory model of the human skin (skin model)
- Measuring the thermal resistance (heat insulation) and determination of the water-vapour resistance of the complete clothing systems using the thermoregulatory model of the human being (thermal manikin "Charlie")
- Determination of the application area of the clothing systems under defined climatic conditions with the help of clothing-physiological predictive calculations

Table 3: Test samples

Description	Clothing system 1	Clothing system 2
Material structure:	Two-layer material structure (shell fabric + filter laminate containing activated carbon)	Two-layer material structure (shell fabric + filter laminate containing activated carbon)
Activated carbon component:	Activated carbon fabric	Activated carbon spheres
Tailoring:	Two-piece (jacket with integrated hood and trousers)	Two-piece (jacket with integrated hood and trousers)
DB3 method and vapour test acc. to TK-BA 34-8415-048	>6 hours	>6 hours

Table 4: Mechanical-technological parameters of the test samples*

Parameter	Clothing system 1	Clothing system 2	Test according to
Surface weight (g/m²)	467	558	DIN EN 12 127
Air permeability (mm/s)	127	63.2	DIN EN ISO 9237

** Tested on the shell fabric in combination with the filter laminate*

4.1 Quantitative Measurement of the Wearer Comfort

The measuring methods described in detail hereafter *[Table 5]* were applied for the quantitative determination of the biophysiological parameters of the clothing systems.

Table 5: Applied measuring methods

Measuring method	Description	Measuring equipment
Stationary measuring method	Thermoregulatory model of the human skin	Skin model
Dynamic measuring method	Thermoregulatory model of man	Thermal manikin "Charlie" of Hohenstein Research Institute

4.1.1 Thermoregulatory Model of the Human Skin (Skin Model)

The biophysical parameters, i.e. thermal resistance (R_{ct}) and water-vapour resistance (R_{et}) of the individual textile layers of the clothing systems *[Table 6]* and underwear *[Table 7]* were determined quantitatively using the thermoregulatory model of the human skin.

The skin model consists of a plate which is heated to the temperature of the human skin. The plate is supplied with water which can evaporate through a large number of pores like the human skin. The skin model is placed in a climate box which can be adjusted to different environmental conditions (such as temperature, humidity and wind speed). This measuring method is established in national and international standards *[6]*.

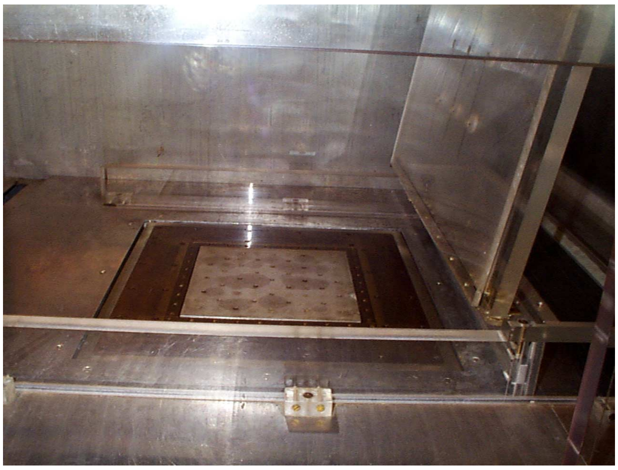

Figure 4: Skin Model, Inside View

Table 6: Biophysical parameters of the test samples

Parameter	Measuring unit	Clothing system 1	Clothing system 2
Water-vapour resistance (R_{et})	m²Pa/W	6.21	10.53
Thermal resistance (R_{ct}) x 10^{-3}	m²K/W	13.1	23.2

Table 7: Biophysical parameters of the underwear

Parameter	Measuring unit	Pants (short)	T-shirt (short sleeve)
Water-vapour resistance (R_{et})	m²Pa/W	3.35	3.78
Thermal resistance (R_{ct}) x 10^{-3}	m²K/W	13.0	13.3

4.1.2 Thermoregulatory Model of Man (Thermal Manikin "Charlie")

A whole-body thermo-dummy was used to evaluate the total effect of the clothing systems including the interaction between underwear *[Table 6]* and outerwear under conditions which are as close to reality as possible *[Table 7].*

The life-size manikin "Charlie" (Hohenstein Research Institute) has a human shape and is a size 50 (medium size), it has mechanically movable arms and legs, and represents a thermoregulatory model of man. It can be provided with the body and skin temperature of man by electrical heating lines in the inside of the manikin's body. In addition, the quantity of heat leaving the body of the manikin and passing through the clothing can be adjusted. This makes it possible to quantitatively determine the heat insulating effect of the clothing systems possible in a certain environmental climate. This climate is adjusted in the climate box in which the manikin is placed.

Figure 5:
Thermal manikin "Charlie" wearing underwear

Figure 6:
Thermal manikin "Charlie" wearing clothing system 1

Figure 7:
Thermal manikin "Charlie" wearing clothing system *2*

The following combinations (underwear, protective equipment components) of the clothing systems 1 and 2 were tested on thermal manikin "Charlie" *[Figure 5]*:

Underwear: Pants (short), made of 100 % CO
T-shirt (short sleeve), made of 100 % CO

NBC protective equipment: NBC protective mask with NBC filter
Cotton under-gloves
Impermeable NBC protective gloves
Socks made of 80 % CO/ 20 % PA
Field boots
Impermeable NBC overboots

Table 8: Chosen climate conditions

Parameter	**Value**
Temperature:	+40 °C
Humidity:	30 % r. h.
Wind speed:	1 m/s

A metabolic rate of **M = 280 W** was chosen for the tests. This is equal to a typical average activity while wearing NBC protective equipment.

4.2 Results

Together with the Skin Model test *[Table 6 and 7]* and predictive calculations, the wearer-physiological application area and the time-pattern of rectale temperatur of the clothing systems 1 and 2 at defined climatic conditions *[Table 8]* and work intensities (M = 280 W), was determined.

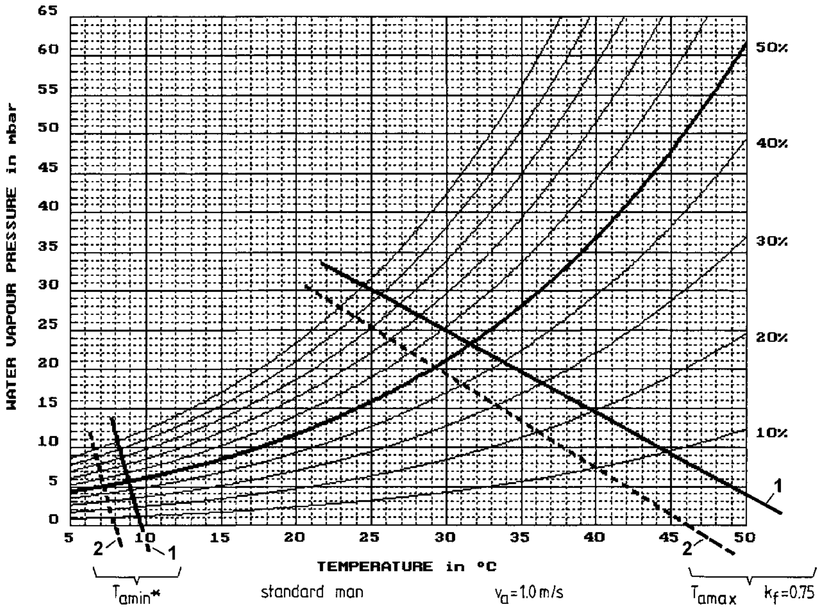

Figure 8: Wearer-physiological application area
——— Clothing system 1
---------- Clothing system 2

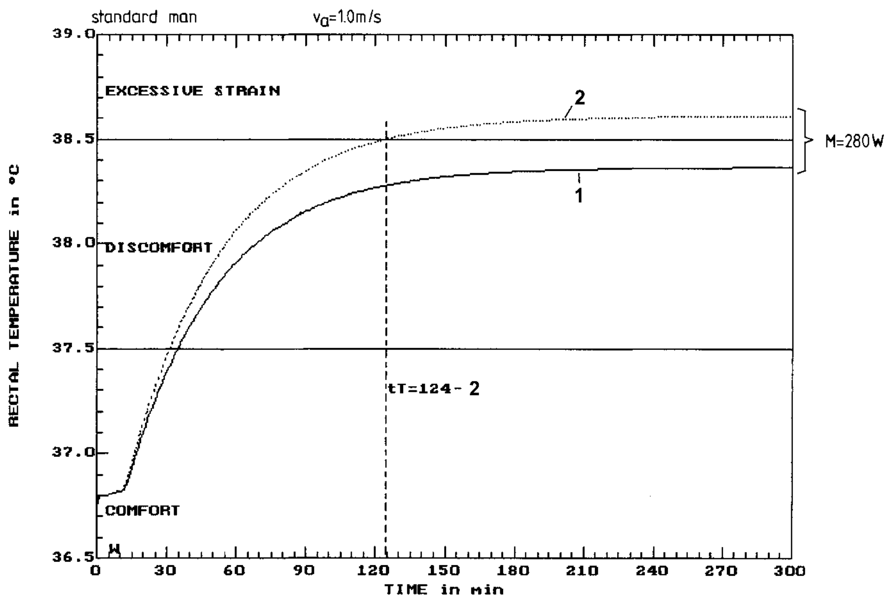

Figure 9: Time-pattern of rectale temperature
——— Clothing system 1
---------- Clothing system 2

5. Discussion

Whereas both of the tested NBC protective suits are able to protect against specific chemical warfare agents for at least 6 hours they are considerably different with regard to clothing physiology. Under the chosen climatic conditions of +40 °C and 30 % r. h. and taking an activity level, i.e. a metabolic rate of M = 280 W into account, it is only possible to carry out missions under full NBC protection for almost 2 hours (124 minutes) wearing clothing system 2 until the physiological performance limit is reached and the wearer is endangered by collapse. *Only clothing system 1 can be worn in missions of more than 6 hours without putting a critical physiological burden on its wearer.*

The tests prove that it is important for the intended application purpose that

- the textile layers of the NBC protective clothing (shell fabric in combination with the filter laminate) have thermal and water-vapour resistance which are as low as possible

- the textile layers of the NBC protective clothing (shell fabric in combination with the filter laminate) have a high air permeability as much as possible.

Due to the tightly closed openings of the clothing, there is practically no ventilation inside an NBC protective clothing, i.e. there is no air exchange between the mirco-climate inside the suit and the environment outside via the openings of the clothing. Respective tests *[5]* have shown that the thermal resistance is reduced by up to 38 % due to a certain "blow-through effect". This is physiologically favourable in hot climates. However, effective air-permeable NBC protective clothing must always ensure an optimal ratio between the "blow-through effect" and the necessary protection performance against CWA, especially in vapour form. Therefore, this optimal solution can only be achieved by the integration of a homogenous adsorber material depending on the function of the total system and its individual components.

Especially in hot cimate zones, the comfort of the wearer can be considerably reduced while his body core temperature and pulse frequency are considerably increased. As an NBC overgarment is usually worn over the combat suit during a mission, the combination of clothing generated can be compared to a winter uniform with regard to clothing physiology, and does not at all meet the mission requirements of tropical regions. Tests carried out in hot climate zones show that wearing such combinations of clothing leads to heat stress within the shortest time so that the personnel is no longer able to fulfill their military missions. Even relatively short actions under full NBC protection can not be carried out.

The high requirements of reliable NBC body protection can only be realised by a new quality of combat clothing which must optimally combine the advantages of a combat suit with those of NBC protective clothing. The Safeguard™ 3002-A1 individual NBCF protection concept meets these technological requirements.

The combat suit with integrated NBC and F protection is worn directly over the underwear in place of the normal combat suit and at the same time replaces the personal NBC protective clothing (when worn together with the NBC protective mask, protective gloves and overboots). It prevents the wearer from direct skin contact with radioactive fallout, and biological and chemical warfare agents. Furthermore, it protects the wearer against thermal effects in the case of nuclear weapon detonations, incendiary weapons or fire (F protection).

Especially the experiences gained in recent missions of crisis reaction forces and the UN troops prove that surprise attacks such as hostile ambushes without prior warning e.g. with Napalm or self-made incendiary weapons such as "Molotov coktails" make immediate protection against thermal effects absolutely necessary.

Summary

Individual NBC protection can only be accomplished completely and effectively if all influencing parameters are considered separately and in the necessary extent from the beginning. Uncritical treatment of individual aspects and correlations as well as inadmissible simplifications will have fatal consequences.

The duration of actions under full NBC protection depends on the structure of the NBC protective clothing to a large extent. However, it will definitely be limited by the actual environmental influences. In the end, the soldier himself, his actions and decisions are the key to success even when being optimally provided with personal equipment, well trained and able to bear physical and psychological stress.

Together with an NBC protective mask, protective gloves and overboots, a combat suit with integrated NBC protection represents a complete set of NBC protection equipment which can be worn for quite a long period of time without considerable physical stress even under NBC conditions due to its air and water-vapour permeability. Due to its immediate availability it provides the soldier with permanent individual body protection so that the duration of actions under full NBC protection is no longer limited by the protection equipment itself and its negative effect on the fitness of the personnel for combat is considerably reduced.

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New Textile Concepts for Use in Control of Body Environments

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Summary

Double layer, or **three dimensional**, textile constructions have been manufactured for some years by Heathcoat in the form of **spacer** fabrics based on a warp knitted construction and also woven double layer products used in the civil engineering industry. The upper and lower layers of such products are interconnected with common threads during the manufacturing process.

In this paper, I hope to convey the new **functional** products that are becoming available in **double layer constructions** from the John Heathcoat textile company.

The R&D Department at Heathcoat have developed a series of novel composite fabrics based on double layer substrates, categorised for discussion as follows:

Woven:

1. Coated – no spring support
2. Coated with spring support

Warp and Weft Knitted:

3. Spring support, no coating
4. Spring support, coated both faces.

A specific design is chosen for weaving the following Category 1 fabric so that the **single and double layer sections** are formed in **alternating rows**. A specially controlled application of an **impervious coating** is then bonded to one face, as shown in *Figure 1.*

If the **cavities** formed by the double layer sections are sealed at one end and **air is blown into the open ends**, the selected porosity of the non-coated face will allow **inflation** which forms a series of **cylindrical cavities; air** will then issue from the **whole area of the porous face** of the cavities. An application of this concept has been developed with MAFF funding, and demonstrated to be very effective, for the **localised cooling** of food on conveyer lines. In addition to maintaining the chilled state of the food, **bacterial challenge** studies found virtually **no contamination** of the area from a high concentration of **introduced bacteria.**

A major benefit of this system is that it allows the **operative** to work in **ambient temperature** conditions since there is not a need for the current practice of chilling the whole room.

Other areas of application are being pursued where localised control of temperature and bacterial contamination are of interest.

The **limiting characteristic** of this category product however is that, in applications where the localised air delivery product is likely to encounter **points of external pressure** to the surface or **sharp bending** of the fabric, the inflated **cavities will collapse** at those points and **restrict or prevent air-flow** along them. To overcome this, **helically coiled plastic springs** are **inserted** into the double layer cavities.

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A range of springs, made from **Delrin acetyl resin**, have been investigated with the help of DuPont polymers and *Figure 2* shows just a few of the **profiles** produced. Typical diameters are 5 to 10 mm.

The **modified properties** of the composite, imparted by the springs, are **unique** and open up **new functionalities** for garments and footwear.

Category 2 consists of double layer woven fabric with an **impervious coating** on one face **as before** but now with the **plastic springs inserted** into the cylindrical cavities.

If air is supplied, through a manifold, into the ends of the cavities it will issue from the whole of the porous face of the composite, see *Figure 3.*

This concept is being developed by the **Defence Logistics Organisation** in the UK, who have funding from the MOD for **optimising the design** of a **microclimate garment**. This will incorporate work by **TNO** in the Netherlands, who will continue the human factor studies in their environmental chamber trials, and composite optimisation by Heathcoat. Such a **forced air** system would allow **natural cooling** of the body through **latent heat** of evaporation of sweat and **Hohenstein skin model** studies will also be made by **DLO.**

The use of coiled plastic springs, as opposed to perforated plastic tubes for instance, maintains the **essential textile characteristics in the product** of flexibility, stretch and drape whilst showing, with the springs used so far, a **crush resistance** of greater than 20 tons per square meter. This means that a person can **lie**, **sit** or **stand** on the product without collapse of the air-carrying cavities. Garments containing such panels are **durable** to being washed in a domestic washing machine.

Figure 4 shows the first **demonstrator vest trials by TNO**, in conjunction with **past studies** done by Defence Clothing and Textiles Agency on **air-cooling garment**s, have shown that this composite structure fabric is the **way to proceed** for a **practical microclimate system** which can be worn by the **dismounted infantryman.**

Re-design of a number of features is planned. For instance the **re-chargeable power pack**, which currently weighs a reasonable **800g**, could be **significantly lighter** in weight with the **same power output** if the most modern battery systems are used. The **portable system** would last for **eight hours** in the field before any re-charging of the power pack **at the vehicle** is needed.

The air delivery **manifold system** from the **lightweight plastic pump** and **filter unit** will be **condensed into the garment** probably as a spring supported fabric tube and, if necessary, **replaceable silica gel sachets** will allow **dry air** to be supplied over the skin in conditions of **high ambient humidity.** No problems are expected with air filtration situations since the **rate of air exchange** demanded by this system is **relatively low.**

The **initials trials** by TNO have demonstrated the need for improvement in **ease of escape** of the delivered air **from the skin surface** and this is expected to be achieved by **cutting away** sections of the **coated layer in the fabric;** this would leave **alternating air delivery sections** and **air escape sections**. Such an arrangement would also allow the microclimate garment to be worn **without extra heat stress** if the portable **air pump system fails.** See *Figure 5.*

Figure 6 shows Category 3 composites that consist of **open mesh** warp knitted double layer fabrics **without** an impervious coating but **with springs inserted.** This creates a **very light-weight** separator product with **very high crush resistance** for environments where an air gap has to be **maintained** even when **high external pressure** might be encountered. This type is under development for **aesthetically acceptable impact protection pads**.

Category 4 development (see *Figure 7*) incorporates the Category 3 product shown on the previous slide. **Gas impermeable membrane** such as butyl rubber, is bonded to **both faces** and **sealed** round the edges except for a **one way valve.** Air is withdrawn from the **whole enclosed cavity layer** to create a high vacuum. **Total vacuum** is easily possible without the springs collapsing and since the **material volume content** in the cavity is **less than 5%**, there is more than **95% vacuum space**. With the presence of an

aluminised outer surface for **reflecting** heat, the opportunity for **heat penetration** through the composite is **minimised.**

The product offers a **unique**, very **flexible**, **wrap round vacuum layer** for **heat** and **sound insulation** and has potential application in **preventing heat loss** or heat **gain** in **blanket** or **garment** type products.

Further **concepts** covered by this series of **patents** involve effects from **rotating the springs** in the fabric cavities in **two different modes**. Textile fabric constructions are possible whereby very **open surface cover sections alternate** in the double layer cylindrical cavities with **more solid cover areas**. If the springs are designed to **coordinate in their shape** with this arrangement of the fabric, **rotation** of the springs in a **non-**screw manner will **open and close the windows** in the fabric, shown in *Figure 8*. If the rotation of the springs is **controlled by temperature sensors**, an **intelligent** fabric will result which has a **variable climate and would** react to **prevailing climatic conditions.**

An **intelligent chameleon effect** can also be produced using springs which have **stripes of three different colours** around their circumference. Rotation of the springs in **a screw fashion** will present a new colour impression to the windows with each **one third revolution** of the springs in the fabric.

Other novel functionalities with these constructions are in **skin surfac**e, or other surface, **vacuum effect** and also for **fluid drainage** from the body.

These concepts are covered by the following Heathcoat patents:

•Gas Delivery Device: EU App. No. 97308535.0

•Fabric with Helical Support: EU App. No. 99309484.6

•Adaptive Material: EU App. No. 00301728.2

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•Claude Maat: Bobet, Rouen, France - Specialist Coating

•Neil Dennis-Purves: John Heathcoat & Co. Ltd. - Research Assistance.

FIGURE 1

CATEGORY 1: WOVEN - COATED

NO SPRINGS SUPPORT

Air inflates the tubes and issues from the whole porous face

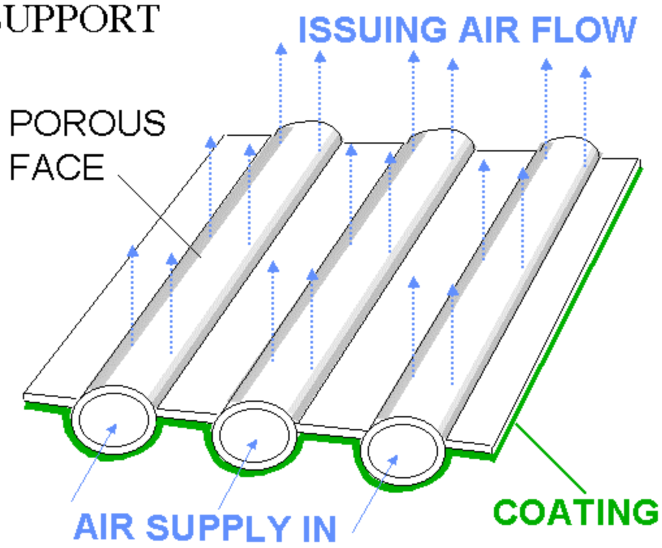


FIGURE 2

SELECTION OF SPRINGS

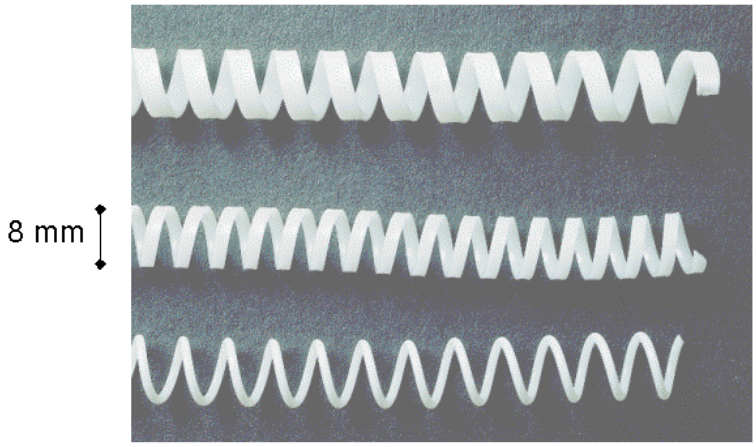
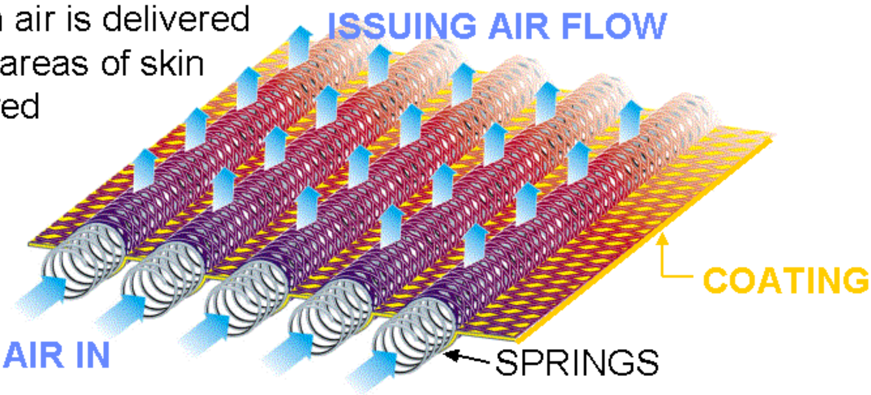


FIGURE 3

CATEGORY 2: WOVEN - COATED

SPRINGS SUPPORT

Fresh air is delivered to all areas of skin covered



The spirals maintain air flow by preventing crushing of the cavities

The material is totally flexible

FIGURE 4

MICROCLIMATE VEST

FIGURE 5 CATEGORY 2 WITH SOME COATED SECTIONS CUT AWAY

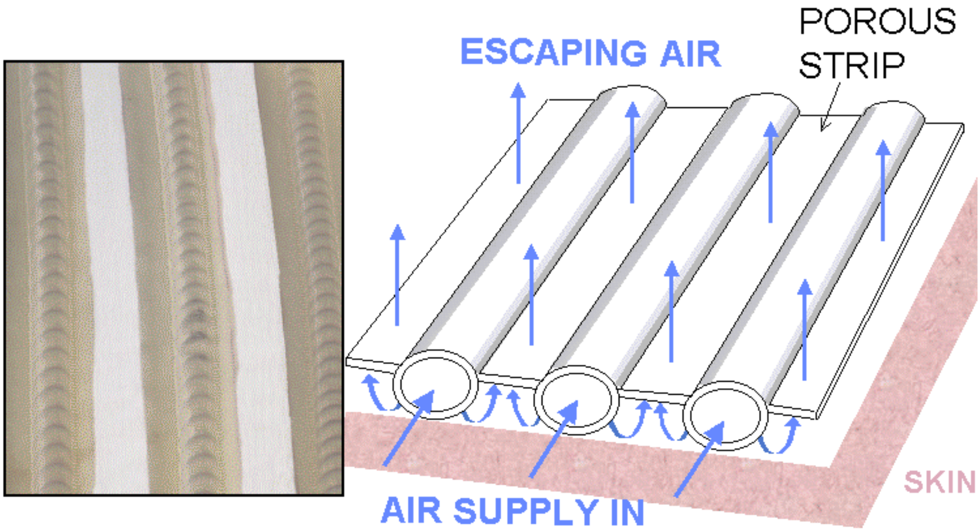


FIGURE 6

CATEGORY 3: KNITTED WITH SPRINGS

NO COATING

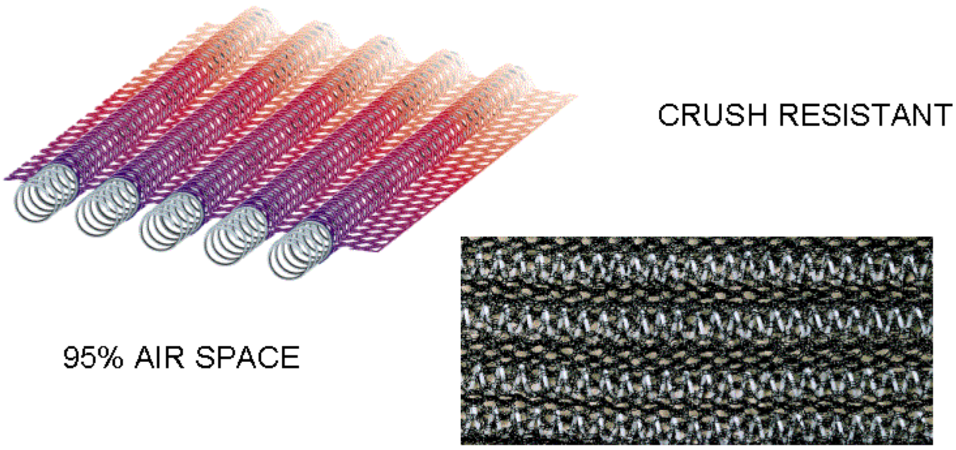


FIGURE 7

CATEGORY 4: VACUUM LAYER EFFECT

IMPERVIOUS BUTYL COATING ON BOTH FACES

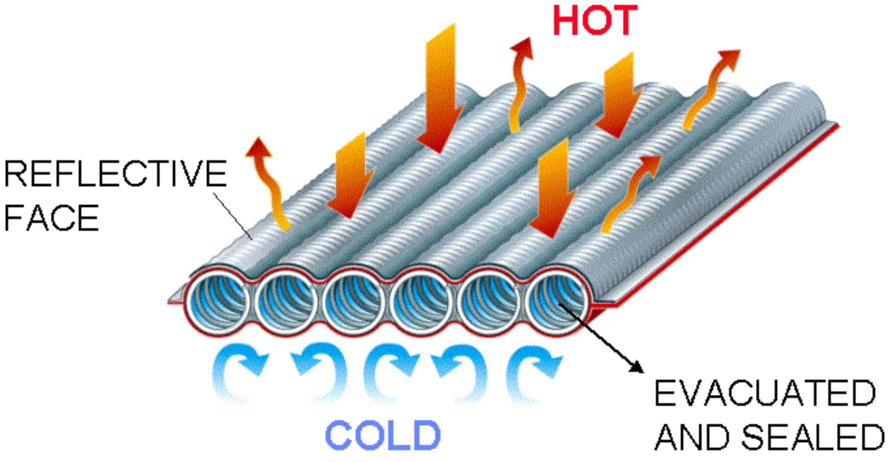
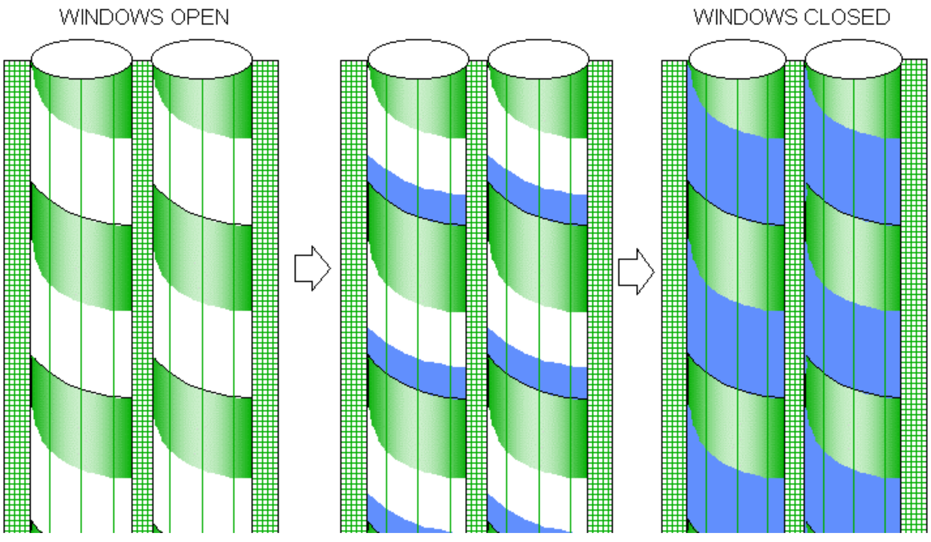


FIGURE 8

VARIABLE CLIMATE FABRIC

SEQUENCE OF ROTATION OF SPRINGS



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U.S. Military Use of Thermal Manikins in Protective Clothing Research

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Summary

The U.S. military has utilized thermal manikins in protective clothing research for nearly 60 years. Prior to their development, the evaluation of textile thermal insulation was limited to one-dimensional, guard-ring flat plates. During WW II, thermal manikins were instrumental in obtaining knowledge of combat clothing ensemble insulation during simulated adverse environmental conditions. Additionally, reports from the various combat theaters regarding the inadequacies of certain clothing components prompted numerous thermal manikin studies resulting in rapid improvement of many combat clothing components before the war's end. During the immediate post-war years, thermal manikin data was used to develop detailed tables of military cold weather clothing insulation and the corresponding climatic zones of issue. During the 1960's, thermal manikin research began to focus on the thermal burden imposed by protective clothing in hot environments. Research using a "sweating" thermal manikin allowed for the measurement of the maximum evaporative heat transfer obtainable by the wearer of a given clothing ensemble. In the 1970's, thermal manikin studies in combination with human wear trials provided the necessary parameters to develop the first reliable equations for predicting core temperature, skin temperature, and heart rate while wearing various military clothing ensembles. From the early 1980's to the present day, extensive research within the U.S. military using thermal manikins has resulted in a vast improvement of all major protective clothing systems for land, sea, and air based personnel. Thermal manikin data also constitutes vital input to several predictive models assessing the amount of thermal stress soldiers will experience during a wide range of environmental conditions and occupational settings. Today, sophisticated thermal manikins are used worldwide in a large number of NATO military and commercial clothing research programs. In the U.S., both the Army and Navy are currently using thermal manikins in a wide range of protective clothing research programs. The U.S. military will continue to rely on these unique research tools to identify advances that will provide future warfighters with more comfortable, functional, and effective protective clothing.

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

Introduction

The U.S. military services have utilized thermal manikins in protective clothing research for over 60 years. Prior to their development, the evaluation of textile thermal insulation was usually conducted in commercial settings and limited to the use of simple one-dimensional, guard-ring flat plates and three-dimensional cylinders. The development of the clo unit in 1941 by Gagge, working at the U.S. Air Force Aeromedical Laboratory, Dayton and Burton and Bazett at the Royal Canadian Air Force Institute of Aviation Medicine, Toronto, provided for a direct, universal measurement of the resistance of textile layers to dry heat transfer (1). One clo unit is defined as the amount of clothing insulation required to keep a normal sedentary man comfortable at 21° C, determined from the partitional calorimetry studies carried out by Winslow et al., in 1936 at the John B. Pierce Laboratory in New Haven (2). One clo is equal to 0.155 $m^2 \cdot K \cdot W^{-1}$.

In 1940, the various military services faced a critical logistical problem in relation to the available stockpile of protective clothing. Most major clothing ensembles had been developed for use during World War I, were composed from natural fiber materials, and were poorly coordinated in terms of providing protection for specific environmental conditions. For cold weather protection alone, there were eleven different uniforms listed with confusing recommendations for use of the 1464 total available components.

World War II-Thermal Manikins Develop as a Result of Global Conflict in Climatic Extremes

As entry into World War II appeared certain, U.S. military planners began to reevaluate much of the outdated and inadequate combat clothing still in the Army Quartermaster supply system. A decision was made to reduce the number of clothing items in the supply system and reconfigure major uniform systems to provide better protection within defined climatic ranges. To accomplish this, there was a need to quantify the thermal insulation of the standard-issue as well as prototype uniforms made from new materials, designs, and fabrication techniques when draped over a human shaped model.

The earliest U.S. military use of a heated manikin was in 1942 by Belding, who had been working under government contract at the Harvard Fatigue Laboratory, Cambridge, determining the comfort-temperature range of sleeping bags and Arctic uniforms for the Army Quartermaster and electrically-heated aviators clothing for the Army Air Force using human subjects. Belding had been using a department store fashion manikin to arrange various clothing ensembles before testing on his subjects. Belding was inspired to build his own manikin to measure the clo values of the protective ensembles he was testing. This crude manikin, lacking both arms and a head, had the general configuration of an obese man and was constructed from sheet copper, sheet metal and stovepipe by a Boston tinsmith. It was heated by means of an electrical heater in the torso and had an internal fan to produce air circulation within the manikin shell. Early studies done with this manikin produced the first clothing ensemble clo values and indicated potential advantages in terms of increased insulation and weight reduction by the use of newly developed synthetic pile fabrics, nylon, and polyester.

With the official entry of the U.S. into the war in late 1942, basic research in the field of environmental physiology and the role played by protective clothing increased tremendously at several newly formed Parallel Service Laboratories (Fort Knox Armored Medical Research Laboratory, Wright Field Aeromedical Research Laboratory, Lawrence Climatic Research Laboratory, Bethesda Naval Medical Research Institute) and at numerous universities (Harvard, Stanford, Yale) around the country. Many prominent environmental scientists (Belding, Darling, Dill, Gagge, Hall, Horvath, Talbott, Wilson) joined the various military services as civilian consultants or commissioned officers.

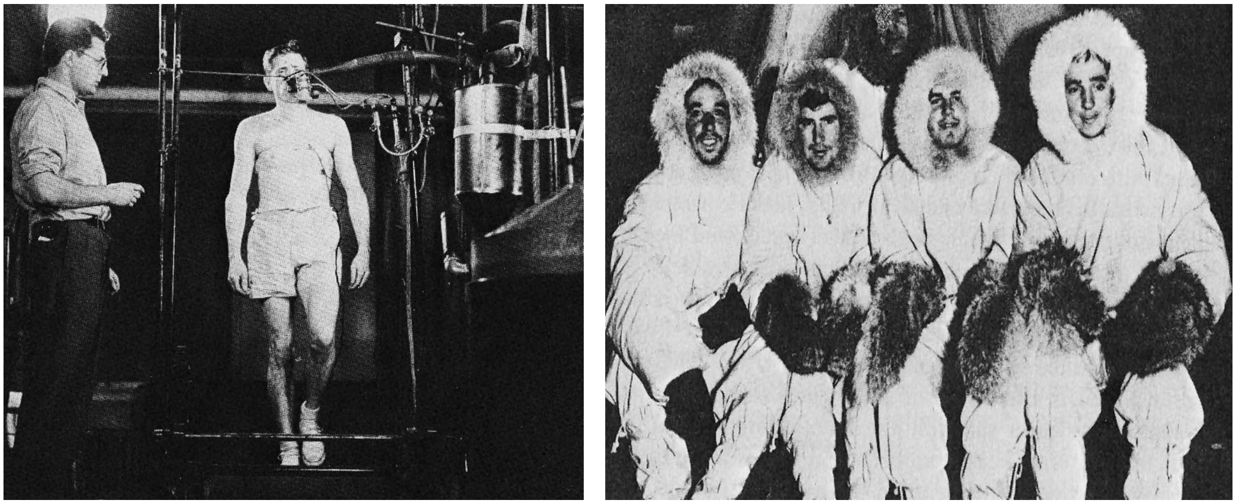


Figure 1. Basic and applied military research was conducted by civilian researchers at the Harvard Fatigue Laboratory in the early 1940's.

In 1943, the U.S. War Department was alarmed at the high incidence of non-combat injuries sustained by U.S. Army personnel sent to retake two Aleutian Islands, Attu and Kiska, that had been occupied earlier by Japanese Forces. Of the 15,000 troops deployed, 2,100 suffered from trench foot and general cold exposure (3). The troops had been sent to this unforgiving cold/wet climate outfitted in World War I vintage protective clothing composed of wool and cotton while wearing uninsulated leather boots. In mid 1943, the Harvard Fatigue Laboratory funded Belding to acquire a more life-like manikin to conduct further studies to improve military protective clothing. Belding contacted researchers at the General Electric Company in Bridgeport, Connecticut. General Electric agreed to construct an electrically heated manikin similar to one they had been using since the late 1930's in their research and development program to develop an affordable electric blanket for the consumer market. This new manikin, cast from the exquisite clay figure done by Connecticut sculptor Leopold Schmidt, was known as the "Harvard Copper Man". The manikin, delivered to the Harvard Fatigue Laboratory in late 1943, was composed of an electroplated copper shell from 3 to 6 mm in thickness and had a single electrical circuit which uniformly heated the actual shell with a provision to vary the temperature of the hands and feet without affecting the surface temperature of the rest of the manikin's body. Belding and his associates at Harvard used their thermal manikin throughout 1944 to evaluate numerous military protective clothing items, investigate reports of inadequacies in protective clothing capabilities coming in from various battlefronts, and suggest possible improvements to the Army Quartermaster clothing specialists. In the process, Belding along with fellow scientists using thermal manikins for Canadian and British military research efforts developed the fundamental basis for today's scientific study of protective clothing.

As World War II drew to a close, many members of the Harvard Fatigue Laboratory including Belding and his thermal manikin joined the Army Quartermaster General's new Climatic Research Laboratory in Lawrence, Massachusetts to continue pioneering work on improving environmental protection for military personnel. In September 1945, General Electric was asked to build the next generation thermal manikin for the Climatic Research Laboratory. General Electric combined its previous manikin expertise along with detailed data from an anthropometric study of nearly 3000 Army Air Force cadets (4) to construct another electroplated copper shell manikin with a total of six separate electrical circuits and based on the average physical dimensions of a young U.S. military recruit. General Electric also delivered a similar manikin to the U.S. Army Aeromedical Laboratory at Wright Field in Dayton where Gagge and his associates used it to completely redesign most Army Air Force aviators clothing away from the use of natural to newly developed artificial materials.

During 1946, researchers at the Climatic Research Laboratory conducted more extensive testing with their new "Copper Man" including very precise determinations of the surface area and surface emissivity as well as nude and clothed clo value studies with the manikin in various orientations, under varying wind velocities, and throughout a wide range of ambient temperatures and humidities. Additional investigations were done in the late 1940's to determine total clo values of most major military cold weather clothing ensembles, standardize the caloric output of the new manikin by evaluating human subjects under similar environmental conditions, and investigate methods to minimize the effects of wind penetration through closures and interstices of outerwear fabrics.

The unique instrumentation, measuring techniques, and theoretical concepts developed during the 1940's allowed for the first effective advances to be made in the research and development of improved protective clothing for the military.

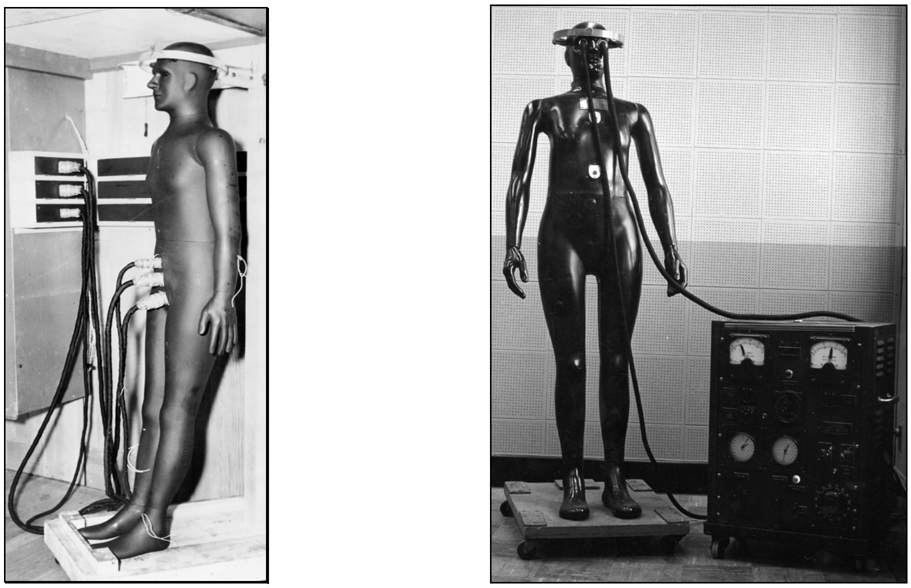


Figure 2. Thermal manikins in use at the U.S.Army Quartermaster's Climatic Research Laboratory in the late 1940's. Left: single circuit "Harvard Copper Man" built by General Electric Co., 1943. Right: six circuit "Copper Man" also built by General Electric Co., 1946.

The 1950's-Worldwide Clothing Requirements Established From Thermal Manikin Data

By the early 1950's, clothing researchers had successfully used thermal manikins to measure the resistance to sensible, dry heat transfer of a wide range of protective clothing from all the military services. In the process, military footwear, handwear, sleeping bags, and combat clothing ensembles were further improved for comfort, durability, and environmental protection.

The Korean War (1950-53), however, again demonstrated the inability of military clothing, handwear and footwear to provide environmental protection for a large-scale deployment of personnel to a harsh climatic region. Severe cold-dry winter conditions on the Korean Peninsula resulted in thousands of cases of cold exposure, trench foot, and frostbite of extremities to U.S. military personnel.

Recognizing that U.S. military protective clothing, including boots and gloves, for use in extreme cold conditions still needed improvement, the U.S. Army Quartermaster in 1951 contracted with General Electric to build two new thermal manikins as well as thermal foot and thermal hand models, again all from electroplated copper. The new thermal foot model, in conjunction with extensive human testing, was used in a successful effort to develop the U.S. Army Extreme Cold Weather Boot in 1953 (6). This boot, which was designed to provide protection at -50° C, had insulation layers hermetically sealed within impermeable layers of rubber and dramatically reduced the incidence of cold injury to the feet of personnel exposed to extreme cold weather.

In 1954, the Climatic Research Laboratory was relocated to Natick, just west of Boston, and renamed the Quartermaster Research and Development Command. This new facility housed military scientist tasked with the research and development of U.S. Army clothing, personal life support equipment, food technology, and airdrop technology. The addition of large climatic chambers in 1955, designed to simulate any climate that military personnel could encounter, further enhanced this facility as the premier military laboratory for protective clothing research.

By 1955, planners from all the U.S. military services had access to extensive tables of specific temperate and cold weather uniform insulation values. These thermal manikin values were then integrated with actual human physiological response data when wearing identical clothing ensembles. At the same time, military earth scientists developed detailed global maps outlining the major climatic zones and their monthly meteorological changes. The result was a series of 25 Protective Clothing Almanacs for each month and every continent that delineated specific areas of use for certain protective ensembles and associated components. This work also produced associated clothing requirement charts, tables, and periodic reports forwarded to major commands to better facilitate the proper procurement and issuance of military protective clothing.

Today, these early clothing distribution guideline efforts have been refined to form part of the Common Table of Allowances, the single Department of the Army document for climatic-based issue of military protective clothing (7).

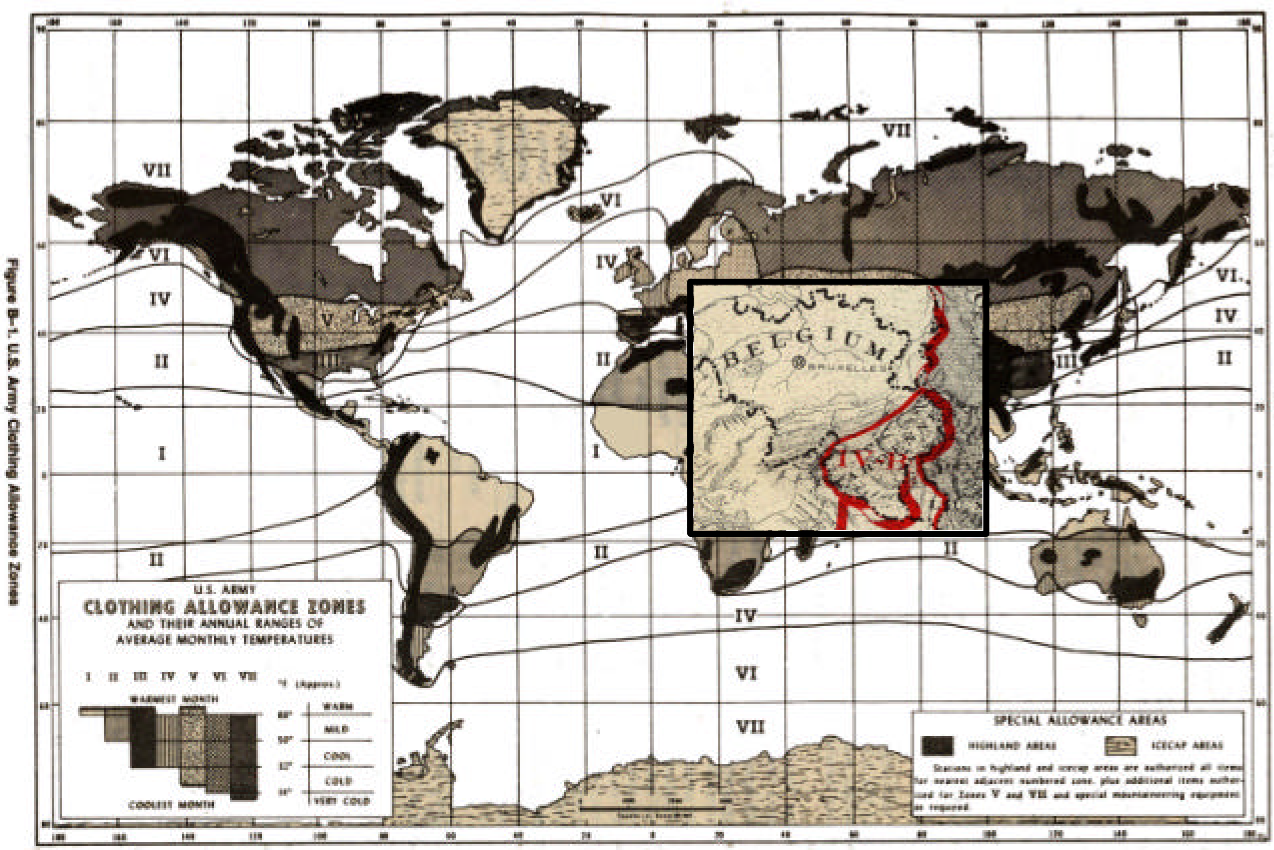


Figure 3. Global and regional maps from a series of U.S. Army Quartermaster General Clothing Almanacs delineating various clothing allowance zones based on local environmental conditions. From reference 5.

Thermal manikin research during this decade also revealed that the highly curved surfaces of the human body created a complex and dynamic microclimate between the clothing and skin surface. Unlike the heat transfer characteristics of textiles established from earlier guarded ring flat plate work, thermal manikins

showed that actual clothing, when draped over the human figure, can have localized variations in thermal conductivity as well as in the ensemble's convective and radiative properties.

The 1960's-Use of Sweating Thermal Manikins to Measure Water Vapor Resistance of Protective Clothing

In 1961, most military thermal manikin work was centered at the new U.S. Army Research Institute of Environmental Medicine (USARIEM) located at Natick, MA. One area of new research was focused on the resistance by protective clothing to the transport of water vapor and its impact on soldier performance. This work was possible due to the introduction of the moisture permeability index, i_m, by Woodcock who was working at USARIEM in 1962 (8). This index is the ratio of the maximum evaporative cooling, at a given ambient vapor pressure, from a 100% wetted surface through a fabric, to the maximum evaporative cooling of a psychrometric wet bulb thermometer at the same vapor pressure. This parameter characterized the permeability of clothing materials to the transfer of water vapor.

Woodcock used a sweating, heated cylinder to conduct his i_m evaluations of both the bare cylinder surface and various protective clothing textiles. Goldman and Breckenridge, interested in utilizing this index for practical clothing applications, outfitted thermal manikins with tight fitting cotton skins that could be saturated with water to simulate a sweat wetted skin surface. These "sweating" manikins could now measure the maximum evaporative heat transfer allowed to an individual wearing a given protective ensemble. This work made it possible to begin a concerted effort to increase the "breathability" of chemical and biological protective clothing as well as assess the thermal burden imposed by the addition of load carriage and ballistic protective equipment to standard clothing systems.

Goldman and his associates at USARIEM proceeded to conduct extensive thermal manikin evaluations on most major military protective clothing systems including a wide range of low permeability garments with and without various combinations of backpacks and personal body armor. At the same time, controlled human volunteer trials were conducted while wearing the same protective clothing configurations in a variety of temperate, warm and hot environmental conditions (9).

Using the knowledge generated by these new sweating thermal manikins of uniform thermal and water vapor resistances combined with the growing data base of human thermophysiological responses while resting and working in stressful environments, it was then possible to rank order military protective ensembles in terms of heat tolerance of the wearer (10).

Figure 4. Technique of using wetted cotton skin on thermal manikins to simulate sweating and measure water vapor resistance imposed by hot weather combat clothing and ballistic protective equipment.

The 1970's-Thermal Manikin Data Used to Assist in Human Performance Prediction.

Comparisons made between thermal manikin data and controlled human volunteer studies indicated that the movement of air within and immediately adjacent to a multilayered clothing system could have a dramatic impact on the evaporative cooling potential of the protective ensemble. Consequently, Givoni and Goldman developed a pumping coefficient (p) that described the effects of wearer-generated air motion on the thermal and water vapor resistances of clothing (10).

Givoni and Goldman then used clothing thermal and water vapor resistances from thermal manikins along with the derived pumping coefficient to develop a series of equations that predicted rectal temperature when wearing military clothing in a range of cool to very hot environments (11). These early equations were further modified by Givoni and Goldman to predict heart rate while wearing protective clothing and working in stressful environments (12).

In the mid-1970's, thermal manikin data continued to be critical coefficient input as these equations were developed into more sophisticated predictive models. Important modifications were made by Pandolf et al. (13) to assess the impact of level of dehydration and by Givoni and Goldman (14) on the effects of acclimatization on wearers of protective clothing.

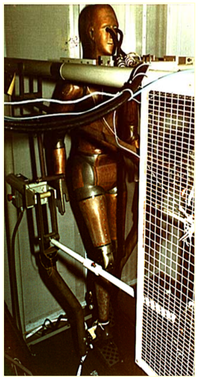
1980 to the Present-Thermal Manikin Data Assists in the Development of Advanced Protective Clothing, Predictive Performance Models, and Portable Environmental Stress Monitors

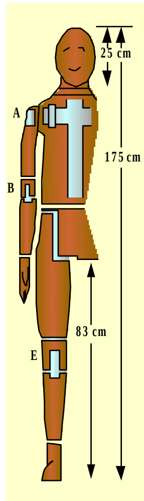
In the early 1980's, the U.S. Army began a complete redesign of major clothing systems for air, ground, and vehicle based personnel utilizing a variety of novel technologies and materials. On an increasing basis, the military has evaluated and adopted numerous commercial textile developments for use in these new combat clothing, footwear, handwear, and sleeping systems. Several U.S. textile manufacturers have specialized, in-house groups interfacing directly with military clothing developers to provide access to novel developments and test results. Military clothing developers were again faced with the ever-present challenge of reducing weight and bulk while increasing the personal protective capabilities of all clothing ensembles and associated components. Numerous biophysical studies were done to evaluate new commercial developments in lightweight, fine-fiber polyester insulations, waterproof/breathable membranes, and durable textiles for use in footwear, handwear and special operations clothing and equipment.

Beginning in 1983, extensive USARIEM thermal manikin evaluations were instrumental in the eventual fielding of the new Extended Cold Weather Clothing System, Intermediate Cold Weather Boot and Glove, all Battledress Uniforms, Joint Services Chemical Protective Suit, and both Intermediate and Extreme Cold Weather Sleeping Systems. All of these new systems incorporate advanced textile materials and design concepts developed in partnership with numerous commercial enterprises located in the U.S. In the past 20 years, USARIEM has provided biophysical thermal manikin data to clothing developers from all the U.S. military services on hundreds of clothing, footwear, handwear, and sleeping systems.

In 1984, USARIEM began using a new articulated, thermal manikin (Figure 5), fabricated by the Arthur D. Little Company, Cambridge under specifications designed by USARIEM scientists. This manikin, employing 19 separate heating zones, has the ability to simulate the bodily movements involved in walking and running. The manikin is housed in a climatic chamber with precise control over the air velocity directed at the manikin. A minimum of three different air velocities are usually necessary to accurately determine the effect of air movement on the thermal and moisture transfer properties of protective clothing ensembles. Table 1. shows typical thermal manikin evaluation data at differing air velocities.

Area and Power Constants for USARIEM Articulated Manikin





	Articulation Section	Surface Area (m^2)	%Total	Design Heat (W)
	Head	0.139	8.3	69.4
	Torso	0.336	19.9	168.0
A	Upper Arms	0.144	8.6	72.0
	Lower Arms	0.062	3.7	31.1
	Hands	0.102	6.1	51.0
B	Elbows*	0.034	2.0	17.0
	Waist	0.020	1.2	10.0
C	Abdomen	0.107	6.4	53.4
D	Right Hip	0.084	5.0	41.8
	Left Hip	0.084	5.0	41.8
	Thighs	0.219	13.0	109.5
E	Knees**	0.052	3.1	26.1
	Calves	0.167	9.9	83.6
	Feet	0.131	7.8	65.5
	Whole Body	1.68	100	approx 500 W/m^2
	Upper Body	0.94	56	approx 500 W/m^2
	Lower Body	0.74	44	approx 500 W/m^2

Figure 5. Photograph and technical specifications of the USARIEM articulated thermal manikin.

SYSTEM	1989 Windspeed,m/s 0.6,"still"			REDONE 1994 1.12			2.24		
	It, (clo)	im	im/It	It, (clo)	im	im/It	It, (clo)	im	im/It
1. IMPERMEABLE BUTYL									
A) WORN ALONE,OPEN	1.58	0.13	0.08	1.36	0.13	0.10	1.22	0.15	0.12
B) WORN CLOSED	2.05	0.08	0.04	1.76	0.09	0.05	1.59	0.10	0.06
C) WORN ALONE, TERRYCLOTH COVERALL	2.05	0.27	0.13	1.76	0.28	0.16	1.59	0.32	0.20
2. FRENCH									
A) WITH INTEGRAL HOOD,OPEN	2.42	0.36	0.15	2.08	0.38	0.18	1.87	0.44	0.23
B) WITH OUT INTEGRAL HOOD, OPEN	2.31	0.39	0.17	1.99	0.41	0.21	1.79	0.47	0.26
C) WITHOUT INTEGRAL HOOD, CLOSED	2.57	0.33	0.13	2.21	0.35	0.16	1.99	0.40	0.20
3. UNITED KINGDOM*									
MKIV					0.00				
A)WITH INTEGRAL HOOD, OPEN	2.18	0.39	0.18	1.87	0.41	0.22	1.69	0.47	0.28
B) WITHOUT INTEGRAL HOOD, OPEN	2.08	0.40	0.19	1.79	0.41	0.23	1.61	0.47	0.29
C) WITHOUT INTEGRAL HOOD, CLOSED	2.27	0.32	0.14	1.95	0.33	0.17	1.76	0.38	0.22
4. THE NETHERLANDS									
A) WITH INTEGRAL HOOD, OPEN	2.35	0.35	0.15	2.02	0.37	0.18	1.82	0.42	0.23
B) WITHOUT HOOD, OPEN	2.23	0.38	0.17	1.92	0.40	0.21	1.73	0.45	0.26
C) WITHOUT HOOD, CLOSED	2.49	0.27	0.11	2.14	0.29	0.13	1.93	0.33	0.17
5. U.S. ARMY BATTLE DRESS OVERGARMENT ,BDO*									
6. CANADA*									

*SEE TTCP REPORT T94-4 also for latest values
UK includes Australia, New Zealand

Table 1. USARIEM thermal manikin data from NATO NBC protective clothing evaluations. From reference 15.

A key development of this research has been the incorporation of thermal manikin data and subsequent clothing coefficient integration into a heat stress monitor (HSM) from 1983 to the present. The miniature heat stress monitor (HSM) is a pocket sized, stand alone electronic device for local heat stress assessment/management. The HSM integrates the USARIEM heat strain prediction model software with a comprehensive suite of environmental sensors and microprocessor technology to provide tailored guidance to reduce heat injury risk across the spectrum of heat stress environments including chemical protective encapsulation.

The HSM has an injection molded plastic case with an integrated hinge and latch closure mechanism. In its closed configuration, HSM dimensions are 12 x 9 x 4 cm. Opening the rear cover allows the sensor module to be rotated into position for environmental measurements, and also provides access to the battery compartment. The system is powered by four standard AA alkaline batteries and has a total weight of 0.37 kg. The field replaceable sensor module assembly consists of air temperature, humidity, wind speed, miniature black globe temperature, and barometric pressure sensors, and their analog/digital processing circuitry. The display is a text and graphics capable liquid crystal display (LCD) and has a back-light feature for use at night. User inputs and HSM function selection are accomplished through a miniature 5 button GPS- type keypad to the right of the LCD. An RS-232 port on the lower side of the case provides PC communications and a miniature threaded tripod mount on the bottom of the case allows secure attachment for unattended data logging applications.

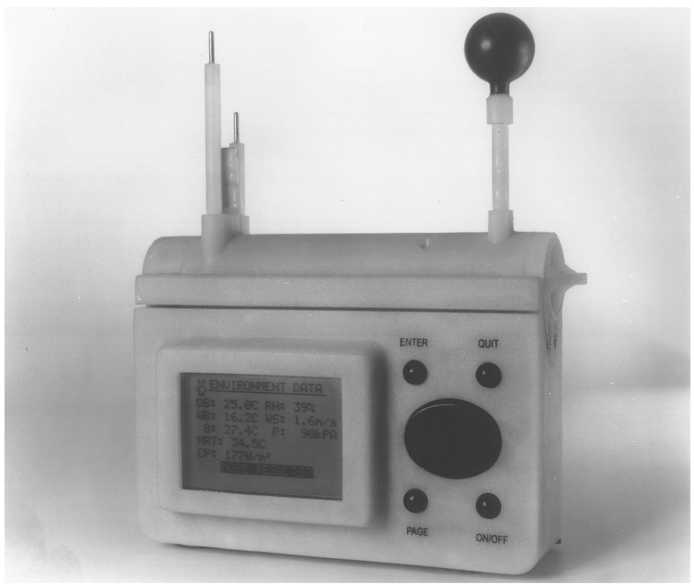


Figure 6. USARIEM Heat Stress Monitor used for prediction of work/rest cycles, water requirements and maximum work possible in any ambient temperature.

The HSM microprocessor system automatically displays current date/time and battery status on power-up. Entering the heat strain model option of the HSM, the user selects menu items for clothing type, work/task category (resting, very light, light, moderate, or heavy work), and acclimatization status (yes or no). After a 2 minute measurement period, the HSM displays hourly drinking water requirements, optimal work/rest cycle limits, and maximum safe work time for continuous work, as well as the 2-minute averaged environmental data used for these computations. A real-time sensor mode may also be selected to view real-time display of air temperature, wind speed, relative humidity, wet bulb temperature, black globe temperature, mean radiant temperature, WBGT index, and barometric pressure. Additional operating modes include: 1) System setup allows the user to set current date/time, and metric or English units for displayed parameters. 2) Datalog setup allows the user select a start time, log time interval, and duration. 3) Datalog review allows the user to view all logged data including predictive model outputs. 4) Data log download allows download of logged data through the RS-232 port to a PC for display with HSM software or import to

a spreadsheet for analysis. 5) Service mode allows PC access through the RS-232 port for program updates, calibration, and system diagnostics.

The HSM is an ideal device that can be employed to help reduce the risk of heat injury in military or industrial settings as well as in sports/physical training applications. The HSM can be used outdoors, in crew compartments and other enclosed work space environments in real-time. With its automated datalog capability, it can also be used to provide operational test documentation or survey data for heat stress conditions over a 24 hour period. HSM measurements of the ambient environment could be used in a variety of human factors engineering/development projects and the programmable microprocessor provides an integrated platform that is easily adaptable for use with a wide range of user-specific models and algorithms.

United Kingdom Mark IV Overgarment
Mask, Gloves, Attached Hood
Ta= 35.0^o C RH= 50% Wind Speed= 1.0 and 4.0 m/s Solar Load

Work Rate	Casualties	Work/HR		Water/Hr Canteens		Max.Work (min)		Water/Hr Canteens	
	Wind m/s	1	4	1	4	1	4	1	4
Light	< 5%	NFW	NL	NA	1.1	108	NL	1.5	1.2
Moderate	< 5%	NFW	22	NA	1.0	49	66	2.1	1.8
Heavy	< 5%	NFW	14	NA	1.0	34	41	2.1	2.1
Light	20%	NL	NL	1.4	1.0	NL	NL	1.5	1.1
Moderate	20%	NFW	37	NA	1.3	69	115	2.1	1.7
Heavy	20%	NFW	22	NA	1.1	45	56	2.1	2.1
Light	50%	NL	NL	1.3	1.0	NL	NL	1.4	1.1
Moderate	50%	13	NL	1.1	1.5	102	NL	2.0	1.7
Heavy	50%	5	32	1.0	1.4	57	77	2.1	2.1

Work Rates: Light= 250watts Moderate= 425watts Heavy=600watts
Work/hr: number of minutes of work with remainder assumed as resting period; NFW= no further work possible; NL= no limit to work times
Casualty Rates: Light= < 5% reaching 39° C core temperature
Moderate= 20% reaching 39.5° C core temperature
Heavy= 50% reaching 40° C core temperature

Table 2. USARIEM Heat strain modeling results incorporating thermal manikin clothing coefficients from United Kingdom chemical protective clothing. From reference 17.

Advanced Predictive Modeling

In recent times, a computer model called SCENARIO, developed by Kraning and Gonzalez (16), has been developed that is specifically designed to simulate the time course of heat strain observed during athletic, industrial, and military settings. The simulations generated by the model dependably reproduce the time course of body temperature shifts, thermoeffector responses, central and peripheral circulatory changes in persons exercising in warm and hot environments. The model also takes into consideration numerous U.S. military protective clothing ensembles that have been evaluated by the various thermal manikins at USARIEM described in this report and is currently being employed to predict physiologic responses for various levels of aerobic fitness in a given population. The model is also currently being enhanced to account for the effects of progressive dehydration. Due to recent standardization of the procedures of thermal manikin operation, different groups can conduct protective clothing research with an increasing degree of confidence in both the compatibility and reliability of interlaboratory data. In terms of continued technological advancement of military protective clothing, numerous NATO countries possess or have direct access to thermal manikins. The U.S. military is routinely involved in various data exchange programs with NATO and The Technical Cooperation Program (TTCP) countries where protective clothing is evaluated and results modeled in a round-robin fashion (17).

Conclusions

Today, sophisticated thermal manikins are used in a large number of military and commercial clothing research programs worldwide. They are routinely used to assess the biophysical properties of consumer, as well as commercial and military protective clothing. Specialized thermal heads, hands and feet are used on a more limited basis for the evaluation of clothing designed to minimize important extremity heat loss.

Since 1942, thermal manikins have evolved within the U.S. military as a direct result of the need to provide better personal protective clothing and equipment in an increasing variety of environmental zones of operation. Thermal manikin data have been instrumental in improving both the comfort and functional performance of a multitude of military clothing and equipment as well as providing input to develop tactical clothing issue doctrine and practical human performance predictive models.

The U.S. military will continue to rely on these unique research tools to test and identify technological advances that will provide future warfighters with more comfortable, functional, and effective protective clothing systems.

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Disclaimer

A Sweating Agile Thermal Manikin (SAM) Developed to Test Complete Clothing Systems Under Normal and Extreme Conditions

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Abstract

Moisture transport, thermal insulation and their interaction influence both the comfort and protective properties of clothing systems. Depending on the environmental conditions and clothing design, wind and repetitive body movements can increase the transport of heat and moisture away from the body. Thus a thermal manikin designed to test clothing realistically, particularly under extreme conditions, should be able to sweat and perform such movements.

SAM is a newly developed thermal manikin capable of simulating even heavy work conditions, with sweat rates of up to 4 litres per hour and human movements such as walking and climbing. The anatomically-formed body is divided into 30 sectors, each heated separately with its own average surface-temperature sensor. In total 125 sweat outlets are distributed over the body surface, with which both vapour and liquid sweating can be simulated over all the body or just chosen parts. SAM is designed to operate at temperatures between –30 and 40°C, with relative humidities ranging from 30 to 95% and up to high wind speeds.

SAM compliments the existing array of sweating body-part simulation systems at EMPA, such as the sweating head ALEX and the sweating torso, by adding the capability of measuring whole-body clothing systems under realistic reproducible conditions and reducing the need for expensive human tests.

Introduction

Thermal manikins are used to help evaluate the comfort and safety properties of clothing. They approximate the thermal nature of the human body and bridge the gap between simple systems to measure thermal resistance (R_{ct}) and water vapour resistance (R_{et}) and the human being, with his repertoire of complex control and sensory systems.

Over the past 16 years EMPA has developed and built a range of increasingly complex body-part systems to measure the thermal resistance of clothing layers with and without the influence of simulated sweat. In 1985, EMPA started to measure R_{ct} and R_{et} separately using the Hohenstein skin-model [1] and developed this to study the influence of rain on R_{et} [2]. This was followed by a heated non-sweating hand, which was built in 1989 to test gloves primarily in cold environments [3]. The sweating arm, built in 1993, is able to sweat and perform simple forearm movements [4]. Shortly afterwards in 1995, the sweating Torso was built to simulate the human trunk [5, 6]. The sweating head (1999) is built to measure the physiological properties of helmets [7]. Finally, following almost 5 years of development, construction of the sweating agile manikin (SAM) was completed this year. A more detailed description of SAM is given elsewhere [8].

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

Traditionally thermal manikins are used to measure the thermal insulation of clothing systems without the presence of body moisture [9]. However body moisture is always present within clothing system layers and effects the total effective thermal insulation.

More recently a handful of thermal manikins have gained the ability to sweat. However the design of the sweating system used and the analysis of results have not yet been standardised [10]. As the newest addition to these sweating thermal manikins, SAM offers a novel internal sweating system, which produces vapour sweating only to simulate insensible human sweating when at rest and combined vapour and liquid sweating to simulate sensible human sweating at high work loads. Although several manikins have moveable joints, or even simple sinusoidal drive mechanisms, the eight-axis drive system of SAM enables even complicated 2-D movements of each limb. Thus realistic human movements can be simulated.

Background

Humans have a complex thermoregulatory system which, under normal conditions, is able to keep the vital organs such as heart, lungs and brain within a narrow temperature band around 37°C. The body produces heat through metabolic processes such as digestion and muscular activity. Depending on the climatic conditions and the clothing worn, excess heat is lost by evaporation, radiation, conduction and respiration.

When the body starts to cool down due to insufficient food, exercise and/or clothing insulation in a cold climate, the body increases its own thermal insulation by reducing the flow of blood to the skin surface, particularly at the extremities. As the sweat rate is also reduced to a minimum (20-25 ml / h, insensible sweating), the heat flow from the body is minimised. Additionally shivering (involuntary muscular contractions) can produce compensatory energy of up to 450 W [11]. Normally the loss of heat through breathing accounts for 10% of the total heat loss, but can increase to as much as 30% in cold climates.

When the body starts to overheat, vasodilatation allows warm blood to flow near to the skin’s surface over the whole body to maximise the heat flow from the body particularly from the extremities. Additionally the overall rate of sweating increases. If this sweat is able to evaporate, the body losses additional heat. The evaporation of 1 litre of sweat causes a heat loss of about 670 Wh. Over short periods of time, up to 4 litres per hour can be sweated [12].

Soldiers who need to wear or carry protective clothing for long periods of time may also be subjected periodically to heavy workloads. Protective properties against wind, rain, certain liquids, heat, flame, thorns, rocks, shrapnel, and nuclear, biological and chemical weapons (NBC) all tend to increase the impermeably to water vapour. Thus not all the body moisture can escape to the external environment. Over a long period of time the moisture content can build up, which reduces the overall thermal insulation (e.g. [6]). In cold climates, the insulation is ideally a maximum when at rest and a minimum whilst working hard.

Body movements tend to reduce the thermal insulation of clothing systems due to increased exchange of air between the clothing layers (microclimate) and the external environment [13]. For certain clothing systems the thermal insulation reduces exponentially with increased walking step frequency and exponentially with increased wind speed [14]. High wind speeds can press the clothing layers together, reducing the insulating air layers and thus the insulation considerably. Additionally wind may flow through the clothing. For example, figure 1 shows that an increase of wind speed from 1 to 13 m/s can reduce the effective thermal resistance by up to 80% for fleece materials. For some protective (e.g. NBC) suits where openings at the wrists, ankles and neck are closed, the air cannot exchange directly and any moisture must pass through the clothing layers or breathing apparatus.

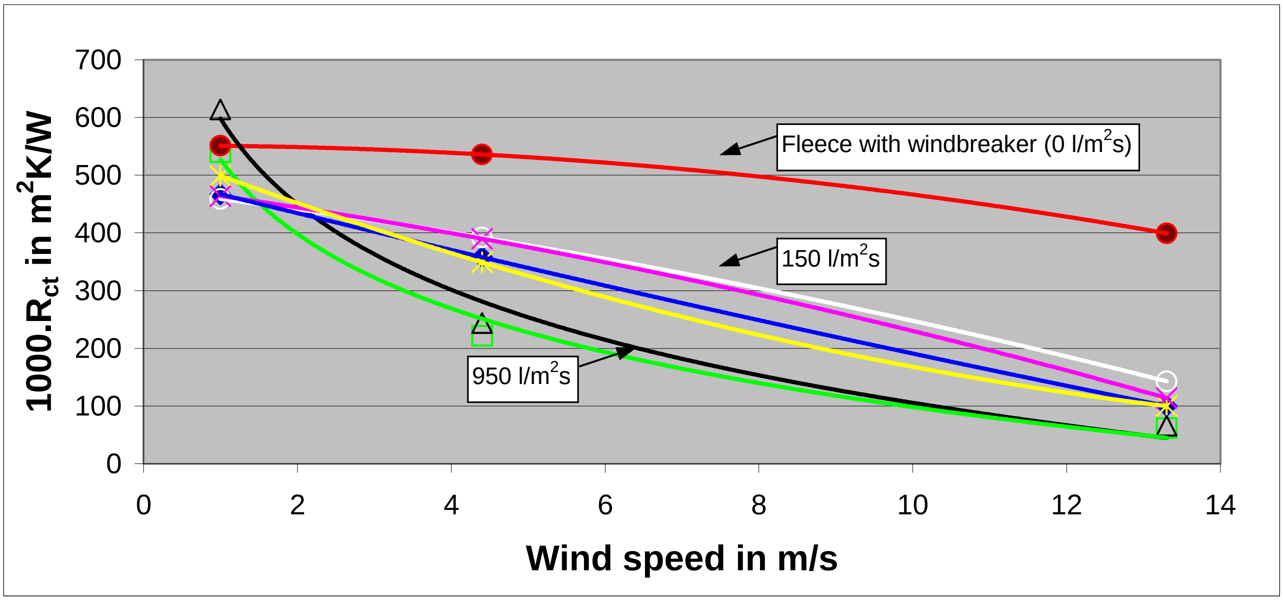

Figure 1 Reduction of thermal resistance with wind speed for various fleece materials measured on the sweating arm. The air permeability is given for three fleeces.

As well as being costly, human tests of clothing systems produce results with poor reproducibility, with results being dependant on many factors including the person being tested, sex, age, diet, sleep pattern, time of day and the activity prior to each test. Furthermore practice tests must often be carried out under medical supervision. Under extreme conditions practice tests can also be dangerous and may even be forbidden by law. By using a thermal manikin, such tests can be performed without the possible risk to life.

Measurement systems built to simulate the human body or body parts produce results with a high reproducibility, but no direct information on subjective human responses such as comfort and pain.
By using a combination of human and system tests, clothing systems can be studied from both psychological and thermal aspects.

SAM's heated sectors
The surface of SAM is divided into 30 separate uniformly-heated sectors (Figure 2). Each sector can be heated at a constant average surface temperature or with a constant power. Thus the whole surface can be heated to a constant temperature to perform standard ISO TC 38 WG17 measurements of thermal insulation or supplied with different heating powers to simulate various activities. A total heating power of up to 1.2kW can be supplied, simulating a very high physical activity as performed by a top sportsman.

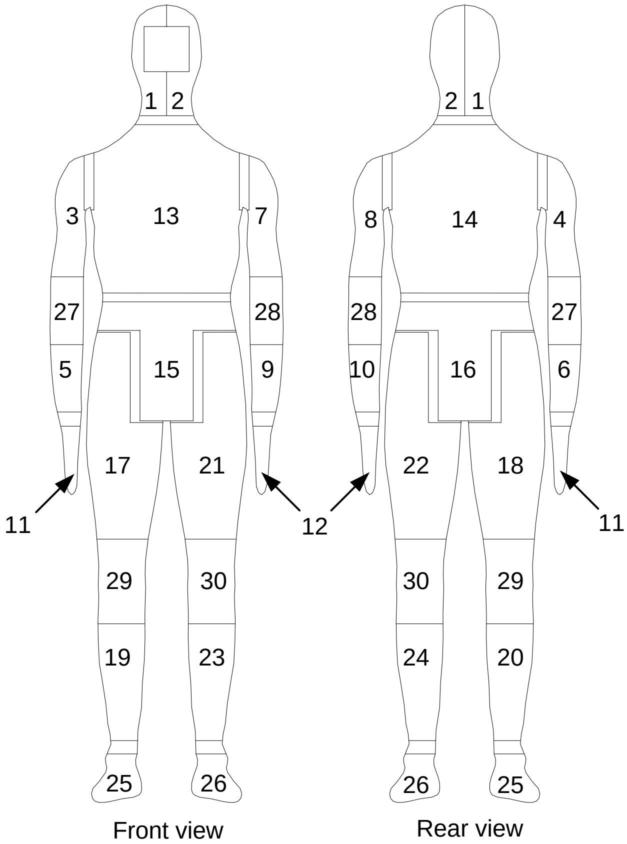

Figure 2 The 30 separately-heated sectors of SAM

Sweating system

SAM has 125 sweat outlets distributed over its surface. Although the human skin has millions of sweat glands, the outlets have been positioned to ensure a sweat distribution roughly similar to the human. Distilled water is used to simulate sweat, supplied through SAM's face to internal valves, which are used to regulate the flow. Special pads which cover the outlets ensure that all the water evaporates at low sweat rates simulating insensible sweating and both vapour and liquid water are output at higher sweat rates to simulate sensible sweating. The total sweat rate is determined with a balance from the reduction of water in the supply tank external to SAM. The total amount of moisture within the clothing is determined by monitoring SAM's weight. The sweat rate can be varied from 20 ml/h up to at least 4 litres per hour to simulate all possible activities and conditions.

Realistic movement system

Much effort has been made to ensure that SAM can perform realistic movements. Joints at the shoulders, elbows, hips and knees enable each limb to be moved in a vertical plane. Each limb is connected to a 2-axis linear drive mechanism. Thus repetitive body movements such as walking and climbing can be performed during an active test phase. Figure 3 shows SAM walking at 2.5 km/h.

Figure 3 SAM walking unclothed at 2.5 km/h.

Measurements techniques

SAM is positioned in a climatic chamber designed to operate at temperatures between –30 and 40°C, with relative humidities ranging from 30 to 95%. A wind generator provides winds up to high speeds and snow and rain can be simulated additionally.

Measurements of the sweat rate and average surface temperature of and average power supplied to each sector are recorded each minute. The total condensate within the clothing is measured at regular intervals. Up to 8 additional sensors (e.g. temperature, humidity, friction etc) may be added to SAM. External temperature and relative humidity sensors are positioned between clothing layers to determine the partial water vapour pressure within the microclimate.

Validation tests

In order to compare the results of SAM directly with the reality, a series of human tests involving 20 young male subjects and 9 different clothing systems has been carried out. As each subject tested each clothing system at least 3 times, over 540 test were performed in total. These tests were divided into 3 categories of different clothing systems representing different physiological loads (Table 1). The first three clothing system results have been presented previously [15]. Results of these human tests will be compared to those of the same clothing systems measured using SAM.

Clothing system		Conditions				
Nr.	Description	T [°C]	r.H. [%]	v_A [m/s]	R [kW/m^2]	M [W]
1.1	Fire-fighter's clothing with compact coating	30	50	2	0.5	350
1.2	Breathable fire-fighter's clothing	30	50	2	0.5	350
1.3	Fire-fighter's station wear	30	50	2	0.5	350
2.1	Clothing for work by temperatures at –20°C	-20	---	2	---	350
2.2	Clothing for work by temperatures at 0°C	0	---	2	---	350
2.3	Clothing for work at room temperature	20	65	2	---	350
3.1	Combat clothing with NBC protection	20	50	2	---	350
3.2	Combat clothing with rain protection	20	50	2	---	350
3.3	Combat clothing with T-shirt	20	50	2	---	350

Table 1 Human tests performed to validate SAM

Discussion

Using steady-state measurements of a thermal manikin, values of effective R_{ct} and R_{et} can be obtained. However in reality humans must perform varying activities in varying climatic conditions. Therefore dynamic responses are also of interest, particularly when predicting the permissible exposure time or survival time under extreme conditions, where the skin and core temperatures are decisive.

As SAM does not have a thermoregulatory system such as the human being, this would need to be simulated using an appropriate control algorithm in order to obtain a similar dynamic response. Such an algorithm must account for the missing blood flow, thermal capacity and breathing. The human body uses a combination of core and skin temperature sensors to regulate blood flow and sweat rate. As SAM does not have an equivalent to core temperature, this may prove to be difficult. Furthermore the distribution of sweat on SAM's surface is only approximate to the human's and relies partly on wicking in the innermost clothing layer. It is planned to model the behaviour of SAM using 3-D computational modelling.

In spite of the differences between SAM and the human body, SAM is capable of comparing different clothing systems under identical conditions and measuring differences in clothing design and manufacture by changing climate and body activity.

Due to the unavoidable spread of physiological data obtained from human tests, tests must be designed to have sufficient physiological load to demonstrate any significant differences when comparing two or more clothing systems. As simulation systems such as SAM produce more repeatable results, even small differences may be significant and small improvements in clothing may be measurable.

Conclusions

Human subject tests of clothing systems are prone to be inaccurate due to variations in human response to even a well-defined scenario. Sweating thermal manikins such as SAM are designed to simulate the human body in terms of heat production, sweat production and movement as closely as possible. Such simulation systems produce results which have a much higher repeatability than those from practice tests, enabling even small differences in clothing to be observed. As a thermal manikin can never truly mimic the human, thermal manikin results should only be interpreted as approximate or indicative or used for relative tests of different clothing systems. Limitations of design such as missing thermal capacity, blood flow control and thus a missing core temperature may be overcome by suitable models. SAM will be capable of comparing the relative dynamic response of clothing systems to body heat, sweat and movement over a large range of environmental conditions, without the inherent costs of human tests and the possible risk to life.

Acknowledgements
This work was carried out as a EUREKA project, being supported by several well-known industrial partners. We wish to thank colleagues of the clothing physiology group for their valuable contributions in the design work and our workshop personnel for carrying out the high-quality construction and assembly work.

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Influence of Body Moisture on the Thermal Insulation of Sleeping Bags

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Abstract

The influence of body moisture on the insulation properties of 10 different sleeping bags, designed for extreme conditions below –30° C, as well as the capability to be used at such low temperatures was investigated in a shared research project of TNO and EMPA. The sleeping bags were assessed with standardised laboratory tests, human subject tests and a system assessment with specialised apparatus. It turned out that the moisture released at such low temperatures leads to condensation within the sleeping bag and ice between the bag and the underlay which reduces the thermal insulation considerably. Even at –20° C both human subject tests and laboratory measurements demonstrate that the sleeping bags investigated have already reached or even exceeded the limit for which comfortable sleep is possible. Details on the limits of use given by the manufacturers are normally based on computer calculations. With two different computer models the calculated temperature ranges were compared to the measurements. It seems necessary to make further investigations in the field of simulation of heat and moisture transfer through complex compositions of textile layers.

Introduction

Sleeping bags intended for use at very low temperatures have to fulfil certain safety aspects, especially concerning the thermal insulation, in order to allow a safe and comfortable sleep. Even at low ambient temperatures when one tends to feel cold a certain amount of moisture, called perspiratio insensibilis (ca. 22 g/h [1]), is released from the body. This moisture normally released in a gaseous state to the ambient air is transported through the textile layers in which it could condense or even freeze. The evaporation of sweating water extracts a considerable amount of energy from the body. At low temperatures up to 80% (see figure 4) of the released moisture condenses inside the sleeping system which reduces the thermal insulation.

Different methods are used to define the maximum range of use for sleeping bags. As this could lead to uncertainties when comparing different sleeping bags it was decided to learn more about the real limits of use. One of the main aims of this project is to study the influence of moisture on the temperature range within which a sleeping bag can still be used comfortably.

Scope of the project

Both research laboratories have been investigating the optimisation of sleeping bags for manufactures as well as the Dutch (Netherlands) and Swiss army for several years [5]. TNO has specialised knowledge and many years of experience in human subjects tests and EMPA offers a wide range of unique test apparatus, which have been partly developed in collaboration with the Swiss army [4]. This project gave a good possibility to combine the broad experience of both institutes in an optimal manner.

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

The series of tests and selections have been divided into three phases:
1: Material measurements of thickness and insulation (TNO and EMPA) for all 10 samples,
2: climatic chamber experiments of human subjects (TNO) for 6 samples selected after tests under point 1 and
3: tests with special test apparatus (thermal manikins) (EMPA) with all samples at different conditions;

No.	Filling material	weight [g]	thickness (at different pressures) in [mm]			thermal resistance [m^2K/W]	
			15 Pa	2000 Pa	1500 Pa	unstressed	at 2000 Pa
1	Synthetics	2624.5	67.0	6.9	10.9	1.133	0.178
2	Synthetics	2747.9	39.2	8.0	12.3	0.718	0.235
3	Synthetics	3116.8	61.0	9.0	12.4	0.923	0.240
4	Synthetics	2282.1	59.9	6.5	12.5	0.810	0.196
5	Downy feathered	1852.0	56.5	6.0	7.0	1.004	0.176
6	Downy feathered	1809.2	63.8	7.0	11.1	1.248	0.174
7	Synthetics	3462.0	58.7	7.0	11.0	0.882	0.200
8	Synthetics	2433.5	66.8	8.0	9.2	1.186	0.240
9	Synthetics	1956.5	61.3	8.0	15.1	0.895	0.230
10	Synthetics	2464.0	46.8	7.5	12.8	0.694	0.210

Table 1: details of the tested sleeping bags

Most of the tested sleeping bags had a nylon outer shell, a synthetic isolation fleece and a skin-friendly inner layer. Within the sleeping bags tested were also two bags containing down feathers (no. 5 and 6). Both the thickness assessment and the thermal resistance measurement have been performed uncompressed and at a pressure comparable to the human weight (between 1500 and 2000 Pa). Corresponding to the different heat transfer mechanisms the uncompressed thermal resistance was assessed with one calorimetric plate toward ambient air (close to ISO 11092) whereas at 2 kPa the measurement was carried out with two plates (ISO 5085-1).

The expectation that heavier sleeping bags would show less reduction of the insulation under a certain pressure could not be consequently proofed (table 1). But the down feathered bags lose more insulation capacity under pressure stress than their synthetic competitors. The thickness of the insulating layer is the most important factor for a high thermal resistance, followed by the volumetric weight and the surface properties (thermal resistance to the ambient air).

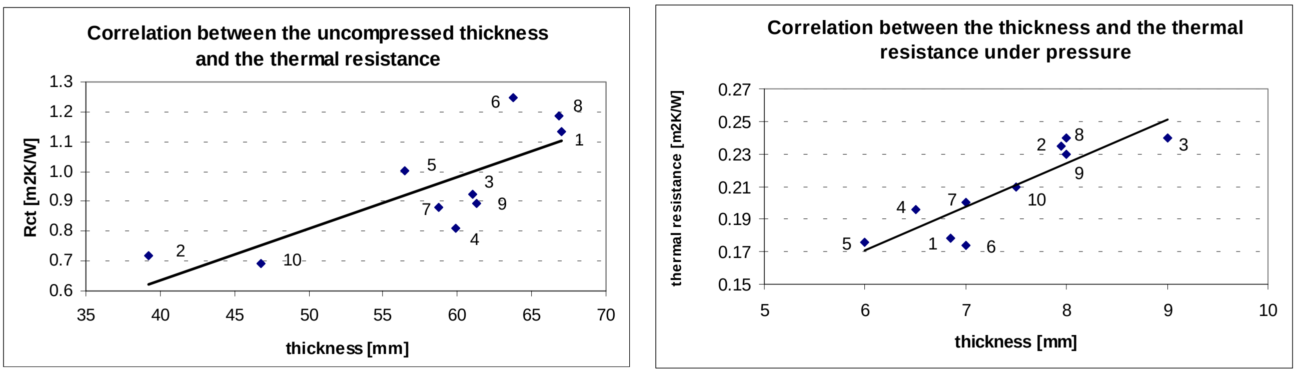


Figure 1: Correlation between the thickness and the thermal resistance at different pressures

In figure 1 it is clearly seen that some of the most voluminous sleeping bags lose most of their thermal insulation under pressure which can be explained by the low volume of material compared to the volume taken up in an uncompressed state.

Sleeping bags as a thermal system

To be able to judge the thermal properties of a sleeping bag in a practical manner the whole system consisting of human subject, clothing, sleeping bag, supporting layer, ground and ambient conditions have to be taken into account. The chosen place to sleep can play a crucial role protecting the sleeper from wind and foul weather. Furthermore it has to be considered that the thermal properties of a human and the environmental conditions can vary over a wide range. As well as the various other boundary conditions the manifold physical and psychological properties of different persons should be standardised for general considerations. This can be done by choosing specific human subjects and using a climatic chamber or by applying specialised apparatus under laboratory conditions.

Generally thermal loss can be classified according to physical criteria such as radiation, conduction and convection. Possible losses in sleeping bag systems include: conduction toward the ground, conductive and convective losses toward the sky, energy transfer through respiration and the influence of the evaporation of sweat. As mentioned above the sweat influences the thermal system mainly through the energy exchange for evaporation and condensation and the reduction of insulation due to replacement of insulation air by water. The evaporation extracts energy directly from the skin surface, whereas the re-condensation usually takes place in the outer layers. Unfortunately the reduction of insulation and the occurrence of condensation are interactive which makes it difficult to describe the system physically. The closer to the skin the evaporation or the condensation occur the larger the influence of these changes have on the skin temperature. The loss of energy due to evaporation is greater than the regain due to condensation since the latter usually occurs in outer textile layers and does not affect all of the moisture in the system.

Especially at low temperatures the respiration should not be neglected since the inhaled cold, dry air has to be moistened and warmed before it reaches the lungs. This process requires a lot of energy which will be lost with every breath. Under normal conditions the heat loss due to respiration is around 10%, at low temperatures it can be up to approximately 30% [1]. Reducing the breathing hole in the face region can lessen the loss of energy but causes more moisture to remain within the sleeping bag as well.

The design of the sleeping bag is very important, modern sleeping bags are equipped with an appropriate cover of the zipper and a thermal lock in the shoulder region. Without an appropriate underlay the thermal losses toward the ground are considerably higher than toward the sky. In an optimal system the heat loss toward the ground should balance the losses to the ambient air.

Measurements with the sweating Torso

The sweating Torso (figure 2) with its cylindrical shape was constructed to be similar to the human trunk. The individual layers of its surface have been chosen to simulate the thermal properties of the skin as closely as possible. In addition this apparatus can be filled with water to give a more realistic thermal capacity and behaviour for dynamic measurements. With 54 sweating nozzles the surface can be supplied with a defined amount of sweating water. Combined with the accurate temperature control, various work loads and recreation cycles can be simulated.

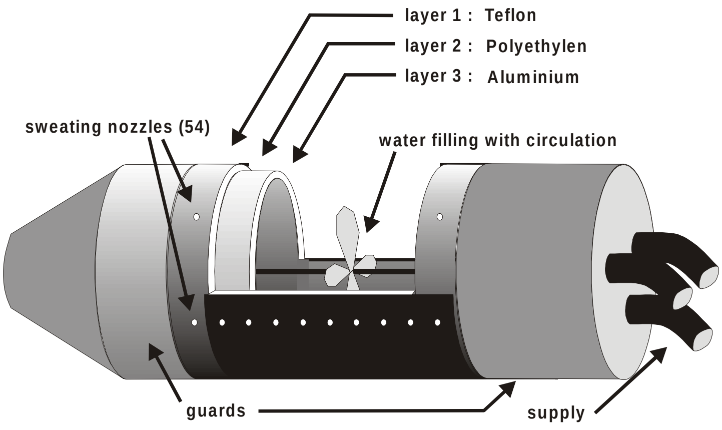


Figure 2: drawing of the sweating Torso

In this project a test program with two phases was defined, consisting of a two hour acclimatisation phase at 35° C without sweating and 8 hours to simulate sleeping with a constant heating power (85 W) and defined sweating (0.3 l/ 8 h). Although all sleeping bags had been acclimatised to the test environment before the test, phase 1 was used to determine the dry thermal insulation under realistic conditions and to guarantee a common starting point for all bags. During the tests the Torso was covered with an underwear (PES fleece) and the apparatus within the sleeping bag was put on a wooden board with a mattress on it. The whole system was positioned on a balance to register all changes in weight within a climatic chamber at –20° C. With this measurement system differences in the temperature course and the weight can be quantified between the 10 sleeping bags. Since the Torso does not have exactly the same thermal capacity and temperature control mechanism as a human body the results should be considered as relative.

In order to obtain more distinctive results the Torso was not filled with water in these tests. Without the water filling the thermal capacity is considerably reduced which lessens the practical relevance of the results in favour of emphasising the differences of the materials. To get results which can be compared to a certain extend with the human subjects tests some tests with water filling were executed.

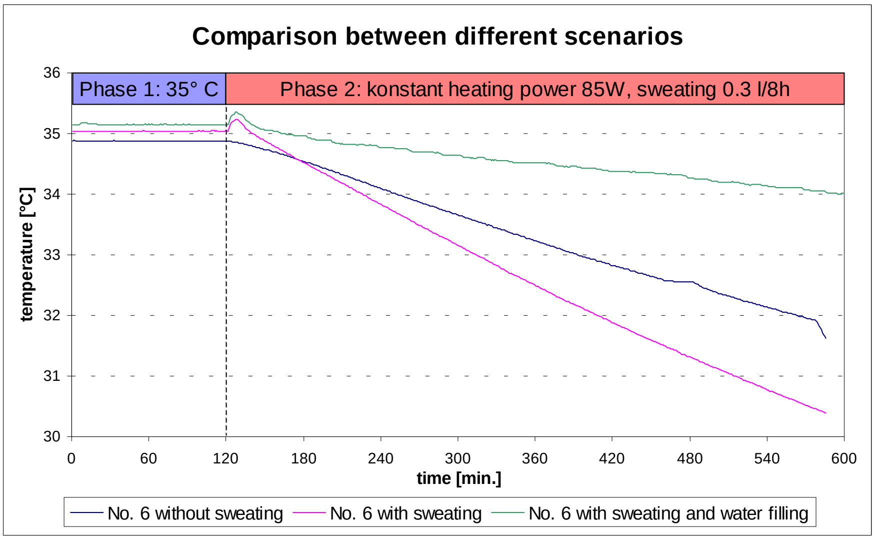


Figure 3: influence of different measurement scenarios on the temperature course

Figure 3 shows the results of the three different measurement scenarios where the effect of the additional thermal capacity can be seen as well as the influence of the small amount of sweat water used in this test. The temperature reduction was diminished due to the additional thermal capacity but still clearly measurable. In another assessment the same test was performed without sweating to demonstrate the influence of the released sweating water on the thermal insulation.

Torso measurement results

In these experiments it was found that at –20°C the Torso cooled down noticeably in all sleeping bags (figure 4).

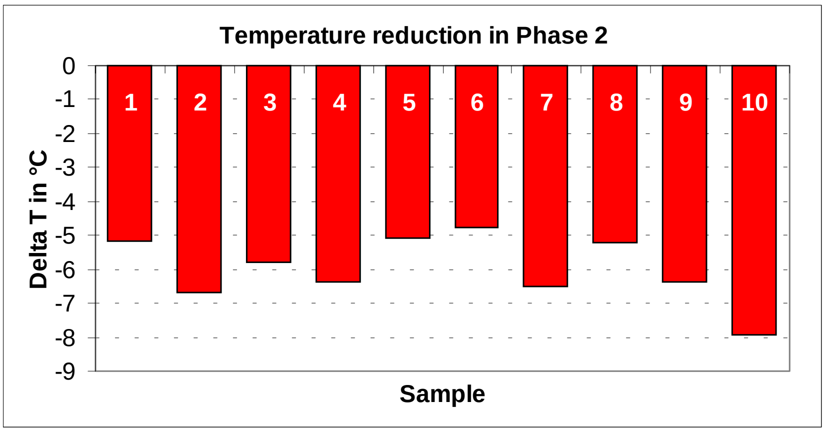
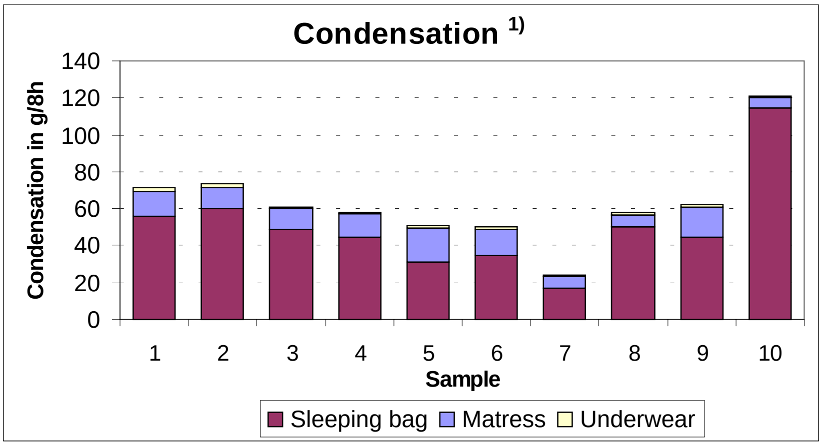


Figure 4: reduction of the surface temperature in phase 2

The measured temperature reduction between 4.8° C and 8.0° C appear to be rather high at first glance, but as the Torso was not filled with water, the results seem to be quite realistic and comparable with the human subject tests (see below). The ranking of the samples is more or less the same as that of the Rct values. Because of the dramatically reduced thermal resistance under pressure a worse result for sample 1, 5, 6 and 8 could have been expected. The matting and the wooden board seem to have compensated for the negative effect of the reduced thermal insulation.

Condensation

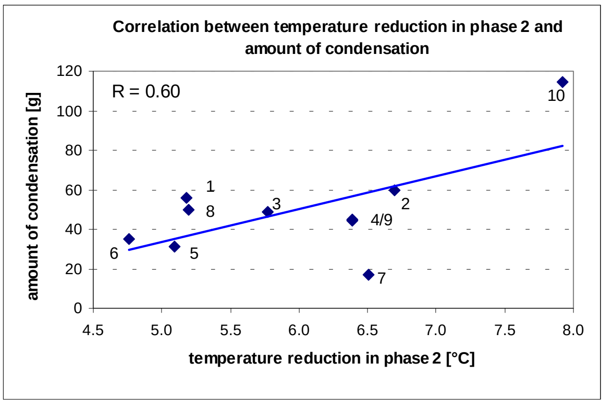
Condensation of the vaporised sweat in a textile layer is provoked by the saturation of the partial water vapour pressure difference and is dependent on the temperature gradient between the body and the environment. A fraction of the energy given up by the evaporation can be recovered but at the same time the thermal resistance is negatively affected by the substitution of air with the condensed water.



1) The amount of condensation is related to the 160 g (20g/h) of totally released moisture in phase 2 of the measurement; the Torso represents only a part of the human body.

Figure 5: amount of condensation in the different layers

At moderate ambient temperatures (> 5° C) and the low sweat rates applied in this Torso measurement programme much less condensation would be expected. But low temperatures hinder evaporation and favour condensation. The measured quantity of condensation varies between 20g and 100g. The sleeping bag with the highest amount of condensation had the lowest thermal insulation. The weak correlation between the thermal insulation and the amount of condensation is shown in diagram 6 (R=0.7). Most of the condensation was found within the sleeping bag and approximately 20 to 30 % in the mattress as ice. In the underwear almost no condensation could be found. Except from sample 7 the down feathered bags (no. 5 and 6) showed the best results in this test.



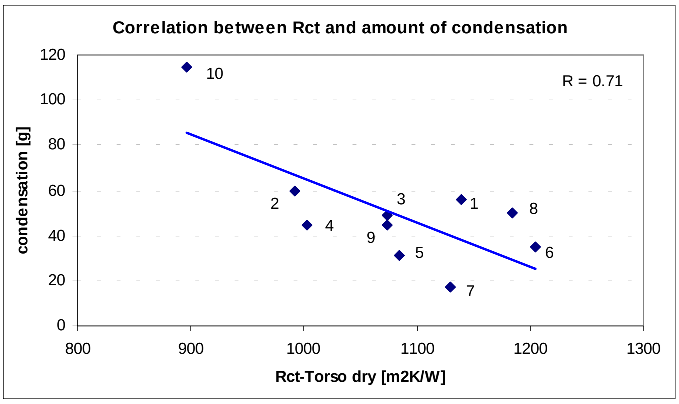


Figure 6: correlation between condensation and temperature reduction as well as the Rct measured on the Torso

Especially in the regions which are compressed the thermal insulation is reduced considerably under the influence of moisture. Measurements on different underwear materials showed that the heat transfer of wet materials is drastically increased depending on the amount of water present [2]. Also the Torso measurements showed a connection between the temperature reduction in the sweating phase, which is a measure for the reduced thermal insulation, and the absorption of moisture at the same time (figure 6).

Human subject tests

If the heat loss remains higher than the metabolic energy production over a longer period of time the temperature of the extremities will be reduced step by step. The vital organs such as the brain, heart and lungs have priority and remain at a high temperature level while the heat losses in the extremities can be reduced. By adapting the posture the quantity of heat loss can be influenced additionally. Laying on the side, slightly rolled up diminishes the contact area with the ground layers and pulling the arms and legs closer to the body reduces the active area for heat exchange with the environment simultaneously. The temperatures measured at the extremities are most suitable to judge the sleeping comfort because changes will be observed there first. Hands are less appropriate due to large movements and corresponding temperature changes. Whereas measurements on the toe or instep promise more accurate results. As soon as the heat loss gets too extensive the self regulative temperature control mechanism reduces the blood circulation which leads to a continuous decrease of the surface temperature at the toe or foot. As a reaction to the temperature reduction in the hands they will be pulled toward the body or placed on the chest which makes this information useless since the temperature on the chest decreases only if the temperature inside the sleeping bag has reached a very low level.

Based on the measurement of the thermal resistance and the thickness, six sleeping bags were selected for the climatic chamber experiments. Human subjects consisted of three men and three women to account for the dissimilar responses of the two sexes to cold environments. All the candidates were fit and between 20 and 30 years old. During six nights the sleeping bags were tested by all six people with temperature sensors on the hand, chest, upper leg and foot at an ambient temperature of –18°C. Besides measurements of the skin temperature, subjective ratings were collected on local and global comfort following every night and then analysed.

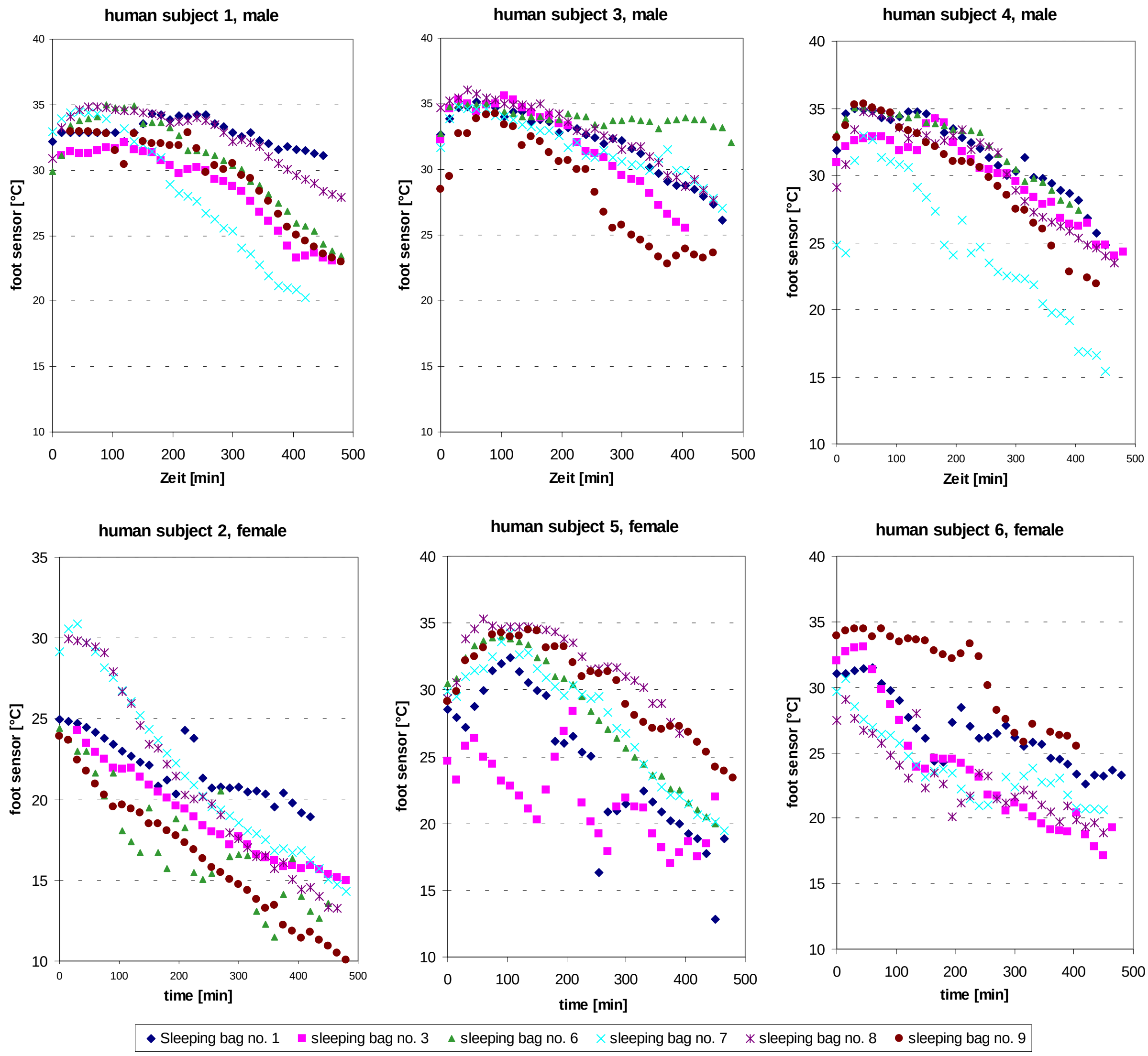


Figure 7: course of the measured foot temperatures

The graphs in figure 7 show the temperature course on the foot for all sleeping bags separately for each candidate. The scattering of the results for each candidate and sleeping bag can not be excluded totally in human subject tests and depends on the current physical and psychological condition of the subjects as well as the activities and meals during the day. For a more detailed analysis of the measured data additional measurements of the same human subjects with the same sleeping bags would be necessary.

Human test results

All subjects complained about cold or very cold feet which corresponds to the temperature courses shown in figure 7 and 8. On the other hand the temperatures measured with the other sensors showed no significant changes. There are noticeable differences between the results from male and female subjects, where particularly the foot temperatures of the female candidates are generally lower.

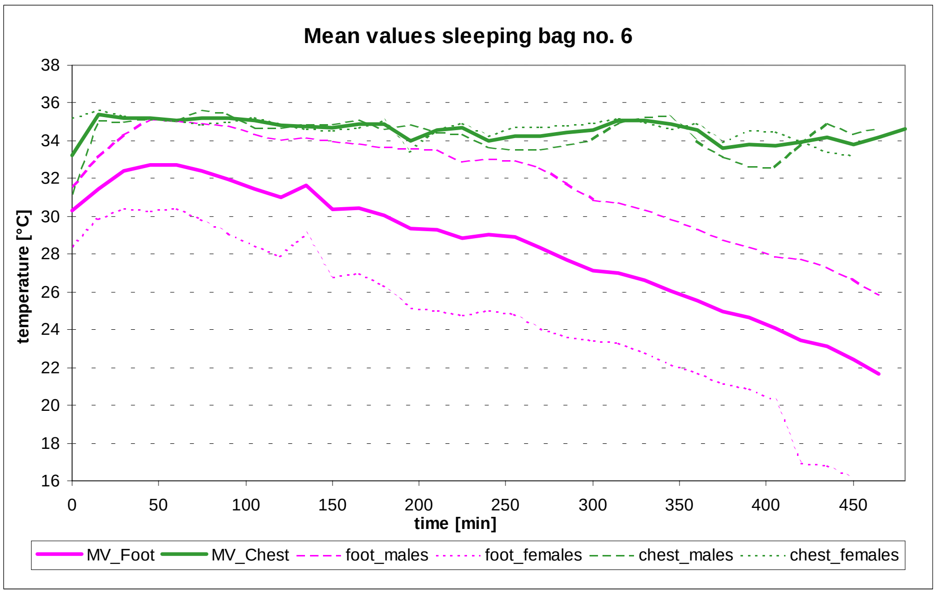


Figure 8: example of the temperature distribution of the foot and chest sensors

Figure 8 shows that for sleeping bag 6 the mean value of the measured chest temperatures remains around the start level, whereas the foot temperatures decrease significantly. The following table attempts to quantify the mean temperature reduction despite the relatively few data sets and the inherent scattering obtained. Relating to the foot temperatures, samples 1, 5 (especially with women) and 6 gave the best results.

No.	Temperature difference foot sensors			Temperature difference chest sensors		
	men	women	both	men	women	both
1	5.6	9.9	**6.8**	0.4	0.6	**0.5**
5	8.4	9.8	**9.9**	4.6	-0.3	**1.6**
6	4.5	10.7	**8.2**	0.2	-0.2	**0.6**
7	9.7	11.4	**10.8**	0.3	-0.1	**0.0**
8	6.3	13.5	**8.9**	-0.6	2.1	**0.8**
9	9.4	11.7	**9.9**	1.0	0.2	**0.3**

Table 2: mean temperature reduction of the foot and chest sensors

Comparison to Torso measurements

A direct quantitative comparison between the two investigations is not possible due to the slightly different boundary conditions and the insufficiencies of the Torso measurements mentioned. The ranking of the sleeping bags matches the measured temperature reductions quite well. Although the Torso was not filled with water and it only simulates the human trunk as well as the fact that the temperature reduction measured in the human subject tests was limited to the feet, the quantitative results show similarities.

Simulation and computer calculations

The range of use of sleeping bags is normally assessed with laboratory tests followed by computer calculations. The models utilised to calculate the limits of use are often based on rough simplifications which neglect the influence of sweating and condensation. A standardised calculation method according to a future European Standard could help solve this problem. The applied calculation models and methods should be accurate enough to allow sensible assessments of the minimal temperature of use.

A simple model used to estimate the lower limit of use

As a first approach the sleeping bag can be simplified to have only two different regions:

- An area on which the body lays where the bag and the underlay will be compressed
- An uncompressed area in contact with the air around the bag

In both cases an energy balance can be set up assuming adequate geometrical and thermal boundary conditions. Taking into consideration the metabolic heat production an estimate for the minimal temperature of use can be calculated. But even if this simple model will be expanded with additional regions between these two main areas some important types of heat loss are ignored. The heat loss due to respiration, where warm moist air is exhaled, and evaporation of sweating water are not included in the balance. Physical models which accurately reproduce these influences can only be realised with complicated computer simulations (see Sweat management project [2]).

Model according to prEN 13537

The proposed European Standard prEN 13537 uses a different method. With a thermal manikin wearing standardised clothes measurements are executed in a climatic chamber under defined conditions. The measured dry thermal resistance is taken as a basis for the calculation of the limit of use adding estimates for the influence of evaporation and respiration to the computer model. The standard calculates 4 different steps using parameters from a standard male and female person: extreme (assuming a person shivering with cold), limit, comfort and maximum temperature (with the zipper half way open). But even with this complex simulation model the results remain a estimate of the real limits. Unfortunately the manufacturers use the extreme temperature to promote their products. Compared with the results of this study the temperatures calculated for the comfort or limit range match quite well with the temperature region where comfortable sleep is possible.

Comparison of the two computer models

sleeping bag	thickness and thermal resistance only	According to EN 13537 based on Rct Torso	
		limit	extreme conditions
1	-8.9° C	-9.6	-27.8
2	-3.4° C	-4.3	-20.9
3	-9.6° C	-7.3	-24.8
4	-9.5° C	-4.7	-21.4
5	-1.8° C	-7.6	-25.3
6	-7.7° C	-12.0	-30.8
7	-7.4° C	-9.3	-27.4
8	-6.5° C	-11.2	-29.9
9	-12.9° C	-7.3	-24.8
10	-6.4° C	-0.8	-16.4

Table 3: calculated limits of use

An additional problem of this simple approximation comes from the complex temperature regulation processes of the human body. The temperatures of different regions of the body can vary markedly depending on the outside conditions. This problem could be partially alleviated by an anatomically shaped, heated manikin with thermal properties like a human and programmed to behave similar to a human. In fact it should not be neglected that the maximal temperature depends on the physical state of the sleeper as well as the additional equipment used and some other factors.

Conclusions

The corresponding results from the human subject test and the measurements on the sweating Torso seem to confirm that none of the tested sleeping bags can be comfortably used at temperatures below –20° C. Without an appropriate mattress the heat exchange to the ground is so high that at such low temperatures one can not sleep for more than a few hours before waking up with cold feet. It also became evident that not all filling materials had the same ability to transport moisture to the outside. The resulting condensation which was considerably higher in some of the samples could cause problems on longer expeditions when the sleeping bags can not be dried during the day.

In this project, the problem of computer calculated temperature limits could only be handled very briefly. The variety of different calculation methods and the sometimes too optimistic results make it necessary to find an accurate rating scheme as well as the mentioned proposal for a European standard. Some of the correlations found could be useful for the development of a simple computer model. The negative correlation

between the dry thermal resistance and the temperature decrease in the second phase of the Torso measurement can be used for that purpose as well as the dependance between the quantity of condensation and the temperature reduction.

Concluding remarks

The examination of the influence of moisture and the interaction of combinations of textile layers show that a fundamental knowledge of the physics involved is essential for the understanding of these processes. Starting with the “Sweat Management” project [2] EMPA began to emphasis computer model calculations and simulations to enhance the knowledge on the complex physical connections. Particularly the effect of moisture is worth examining more closely since this is essential for successful research and development projects with manufacturers or co-operating institutes to find an optimal balance between comfort and safety. The newly built movable, sweating manikin SAM [8] could help to improve accurate tests on sleeping bags due to the reproducible, anatomically correct simulation of a human being.

In this study ageing and durability properties have been ignored. The thermal insulation characteristic is largely influenced by the ability to expand to the original volume following washing or transportation in a small bag. Particularly repetitive washing can reduce the insulation and therefore this aspect should be investigated in future projects. The sleeping bags examined in this study will be subjected to 5 washing machine cycles and tested again. In addition TNO will use some of these sleeping bags for a long period field trial.

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Prediction of Wind Effects on Cold Protective Clothing

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Summary

Cold protective clothing is characterised by its thermal insulation and wind-proof properties. Standard insulation is measured for complete ensembles under static and wind still conditions (ENV-342) Air permeability is measured on the material of the outer layer (ISO-EN-9237). Limited information is available on the interaction of air permeability and thermal insulation under the influence of wind and walking. Ten ensembles comprising 2 to 3-layer combinations with a range of insulation values from 1.49-3.46 clo (0.23-0.54 m^2°C/W) and air permeability between 1 and 1000 l/m^2s were measured with a standing and walking thermal manikin. The manikin was placed in a wind tunnel at wind speeds between 0.2-18 m/s. Walking speeds ranged from standing to 1.2 m/s. One equation was derived for prediction of the reduction in thermal insulation value as function of wind, walking and air permeability. The deviation between measured and predicted value was mostly less than 5 % and below 10 %. Air permeability has limited influence in wind speeds below 3 m/s, but becomes progressively important at higher wind speeds. Typically a three layer ensemble with low air permeability will loose 60-70 % of its total insulation in winds of 12 m/s and higher.
The new algorithm for correction of clothing insulation has been incorporated in (ISO/CD-1179) and subsequently, allows more realistic
- prediction of heat balance in cold environments and operational capabilities
- analysis of the risks associated with extreme cold and wind conditions
- assessment of the protective function of available cold weather ensembles.

Introduction

Air temperature and wind are the two most important climatic factors determining heat losses from humans in cold environments. Studies have shown that the protective value of clothing may reduce considerably under the influence of wind (Afanasieva 1992; Havenith et al. 1990; Mäkinen et al. 1998; Mäkinen et al. 2000; Mäkinen et al. 1997; Nilsson et al. 2000; Pugh 1966; Wilson et al. 1970). Few studies, however, report systematic effects over a wide range of wind velocities.

Cold protective clothing is characterised by its thermal insulation and wind-proof properties. Standard insulation is measured for complete ensembles under static and wind still conditions (ASTM-F1291 1995; ENV-342 1999). Air permeability is measured on the material of the outer layer (ISO-EN-9237). Limited information is available on the interaction of air permeability and thermal insulation under the influence of wind and walking.

This paper reports the result of two studies of wind effects on different types of clothing ensembles, carried out with a moveable thermal manikin. Parts of them have been published (Holmér et al. 1992; Nilsson et al. 1998; Nilsson et al. 1992)

Material and methods

Ten ensembles comprising 2- to 3-layer combinations with a range of total, static insulation values from 1.49-3.46 clo (0.23-0.54 m^2°C/W) were measured. Six of them were measured in a climatic chamber where wind could be controlled between 0.2 and 1.0 m/s (Nilsson et al. 1992). Four ensembles were measured in a climatic chamber with a built-in wind tunnel over the range of 0.4 to 18 m/s (Nilsson et al. 1998). The four ensembles comprised 3-layer systems with different outer garments. The air permeability of the outer garments varied between 1 and 1000 l/m^2s. In both studies measurements were also made with the manikin nude.

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The manikin comprised 18 zones, heated by a computer regulated power supply from an electric power box. Skin temperature was individually controlled and maintained at 34.0 °C. The manikin was placed in a wind tunnel at wind speeds between 0.4-18 m/s. Walking speeds ranged from standing to 1.2 m/s. Walking speed was determined from step length and step frequency. Manikin heat loss was monitored and a valid record was obtained when it had reached steady state (approx. after 40-60 minutes). Manikin and procedures have been reported earlier (Nilsson et al. 1997). The manikin can simulate walking movements by a pneumatic lever system (Figure 1).

$$I_{Tot} = \frac{34 - t_a}{Q_{Tot}} \cdot A_d \qquad (1)$$

The total insulation value was calculated by equation 1. I_{Tot} is the total insulation value in m^2°C/W, 34 is the controlled manikin surface temperature in °C, t_a is the ambient air temperature in °C, Q_{Tot} is the sum of all zone heat losses in W, and A_d is the manikin surface area in m^2. The repeatability of the method, used for determination of insulation values, is high. The difference between double determinations was less than 5% of the mean value of the two measurements based on 228 independent measurements. Insulation values are often reported as clo-values – 1 clo=0.155 m^2°C/W.

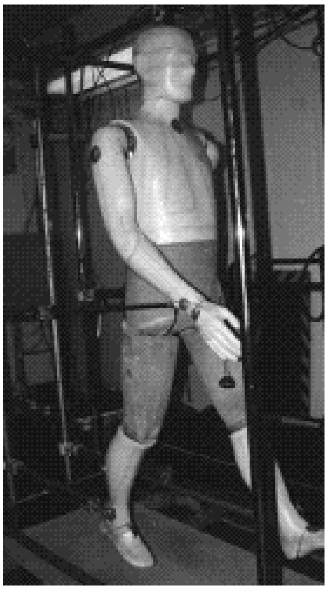

Figure 1. Walking, thermal manikin ”TORE” used in the two wind studies.

Results and discussion

The regression equations obtained with the two sets of data from quite different range of air velocities were remarkably similar. In the range 0.2-1 m/s there was little variation between types of clothing in relative reduction. Data were pooled with the results from the second study with a much larger range of wind velocities. The general equation derived from this data set of 228 independent measurements showed a correlation coefficient of 0.91. The general equation has the form

$$I_{t,r} / I_t = A \cdot e^{(B.v + C.w)} \qquad (2)$$

Figure 2 shows the reduction in insulation value for four ensembles at air velocities from 0.4 to 18 m/s. The reduction is expressed as fraction of the value at 0.4 m/s. The four ensembles represent similar types of 3-layer systems, but with different material in the outer layer. There is a clear difference between ensembles, in particular at higher wind velocities.

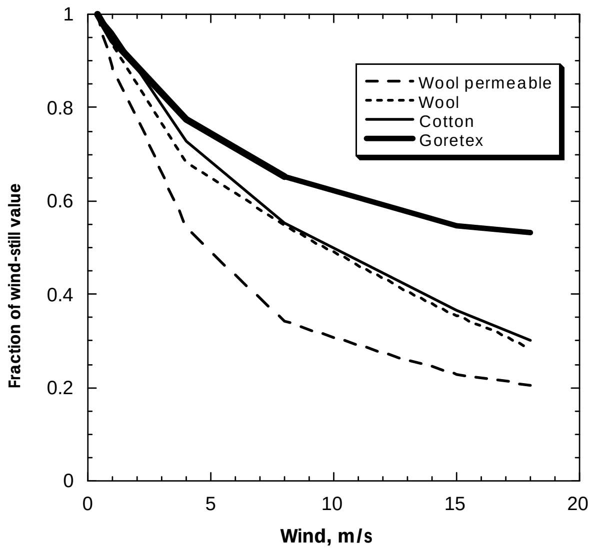

Figure 2. Reduction of total insulation of four types of winter clothing ensembles as function wind speed. Measurements were taken with a thermal manikin in a climatic wind tunnel.

At higher air velocities an equation with only wind and walking as variables becomes insufficient. An obvious reason for this is the air permeability of the outer layer. This material property becomes an important determinant of wind penetration into the clothing layers and subsequently affects the heat losses. Air permeability was introduced in the regression analysis and new equation was derived with the three variables.

The insulation reduction ($I_{t,r}/I_t$) as a function of air permeability (p, l/m^{2}s), wind speed (v, m/s) and walking speed (w, m/s) based on the present data set of is now calculated with:

$$I_{t,r}/I_t = 0.54 \cdot e^{(-0.15 \cdot v - 0.22 \cdot w)} \cdot p^{0.075} - 0.06 \cdot \ln(p) + 0.5 \qquad (3)$$

The equation is derived from three dependent regressions, one for wind and walk (R = 0.885) and one for the inclination of the permeability (R = 0.965) and one for the intercept of the permeability (R = 0.998). The standard deviation of the difference between measured and calculated data ($I_{t,r}/I_t$) is 4% (Max/Mean/Min 15/5/0) based on all 228 independent data sets. The maximum, mean and minimum difference are 15, 5 and 0 %, respectively. The valid interval for the equation is 0.4-18 m/s wind speed, 0-1.2 m/s walking speed and an air permeability of 1 to 1000 l/m^{2}s. The equation is plotted in figure 3 for a low and a high value for the air permeability of the outer layer.

Air permeability has limited influence in wind speeds below 3 m/s, but becomes progressively important at higher wind speeds. Typically, a 3-layer ensemble with high air permeability will loose 60-70 % of its total insulation in winds of 12 m/s and higher (figure 3). Also highly impermeable ensembles will loose 30-40 % at high wind speeds, mostly as a result of boundary layer breakdown and compression effects.

Few data are reported in the literature on effects at high wind speed. Breckenridge and Goldman (Breckenridge et al. 1977) derived specific correction equations for defined military ensembles. At 10 m/s the winter ensemble reduced by about 20 % and the standard fatigues with over-garment reduced by about 40 %. Reductions are a little bit smaller than reported here (Figure 3), but a direct comparison cannot be made, as the details of the ensembles are not known. Afanasieva (Afanasieva 1992) reported wind effects of similar magnitude to those reported here.

Wyon (Wyon 1989) made a series of measurements with a thermal manikin in a small wind tunnel and reported the results as wind chill equations for typical civilian, outdoor clothing. He concludes that the wind-chill temperature for the clothed body is much lower, than for nude skin. This is in clear contrast to the results of this and other studies (Breckenridge et al. 1977; Steadman 1971; Steadman 1984). His results show

remarkable reductions also for heavy winter clothing. The temperature for good heat balance would need to be +2 °C for jogging at 220 W/m^2 in a wind of 2.5 m/s dressed in an ensemble with a total, static insulation value of 2.6 clo (0.403 m^2°C/W). This is in clear contrast to common experience. Using the IREQ-index (ISO/CD-11079 2000) for the given conditions gives a balance temperature of –23 °C. Making the unlikely assumption that the specified down jacket is highly air permeable (500 l/m^2s), still gives a balance temperature of –18 °C.

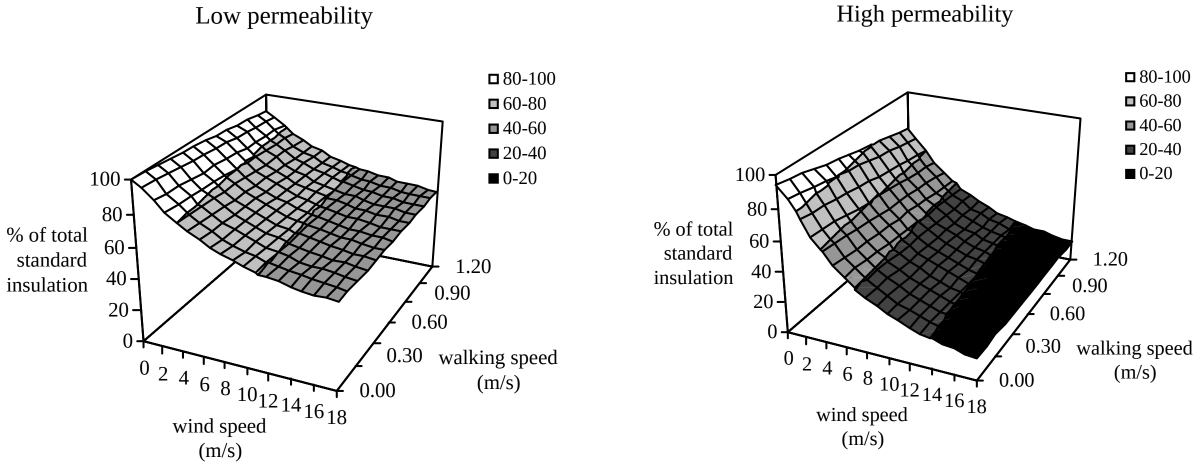

Figure 3. The combined effect of wind and walking speed on the total insulation value of 2-3-layers clothing ensembles. Air permeability of the outer layer is 1 (left panel) and 1000 l/m^2s (right panel), respectively (Nilsson et al. 2000).

The new correction algorithm is used in the revised version of the IREQ-index (ISO/CD-11079 2000). The value of IREQ is still the same (figure 4), because this is the resultant insulation that must be provided by clothing independent of type, material and wind. In order to analyse if the selected (worn) clothing ensemble satisfies the requirement (IREQ-value), the insulation reduction as a result of the given conditions (activity and wind) and the material air permeability must be calculated. This is done automatically in the computer program. This means that the selected clothing maybe required to have a static insulation value that can be more than 2 times higher than the IREQ-value, in particular if wind speed is high and air permeability is high (figure 3). In other words, when tested according to ENV-342 (ENV-342 1998) or ASTM-F1290 (ASTM-F1291 1995) the ensemble gets an insulation value for static, wind-still conditions. This value will then be corrected in the IREQ-analysis using the new algorithm.

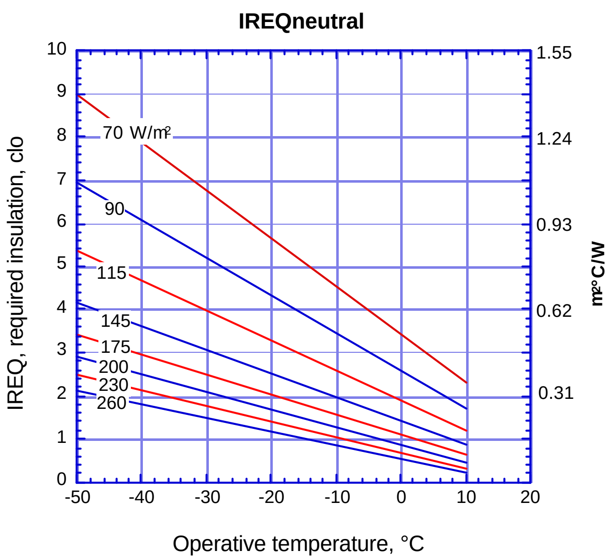

Figure 4. IREQneutral as function of ambient operative temperatureat eight levels of metabolic heat production. IREQ is specified for thermoneutral conditions of the heat balance. This would correspond to a thermal sensation of neutral to slightly warm. Values apply to wind-still conditions.

In conclusion, one equation has been derived for prediction of the reduction in thermal insulation value of 2-3-layers clothing ensembles as function of wind, walking and air permeability. The deviation between measured and predicted value was mostly less than 5 % and below 10 %. The air permeability has little influence on the insulation for wind speed below 3 m/s. For calculations below such a limit the air permeability could be omitted. In the future only measurements on a standing manikin should be needed. The wind, permeability and walk reductions will be calculated from this value. To validate the relationships more measurements on subjects exposed to wind and activity in working life are needed. This is the subject of a recently started EU-research project. Albeit, the correction algorithm is based on a large database, results from the testing of new materials and ensembles, may modify the basic equation.

The new algorithm for correction of clothing insulation allows more realistic
- prediction of heat balance in cold environments and operational capabilities
- analysis of the risks associated with extreme cold and wind conditions
- assessment of the protective function of available cold weather ensembles.

Acknowledgement

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Numerical Simulations of the Flow Around a Circular Cylinder Covered by a Porous Medium

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SUMMARY

In order to develop more comfortable and safe protective garments, it is necessary to obtain detailed knowledge of the phenomena governing air flow, heat and mass transfer. Computational Fluid Dynamics (CFD) is a promising approach for those kinds of problems. Numerical simulations can support the design process and make it cheaper. Simulations of the air flow in a 2D model of a cylindrical human body part covered by protective clothing are presented here. The CFD predictions show dependencies of the air flow penetrating the clothing material, and the heat and mass transfer to the body part, as a function of external flow and clothing material properties. The problem has been formulated by using dimensionless parameters, reducing the number of properties for flow and clothing conditions. The clothing material has been modeled as a porous material. For turbulence modeling, we used an RNG k-ε model. The set of governing differential equations has been solved numerically by use of the commercial flow-simulation code Fluent 5.

INTRODUCTION

Investigation of the phenomena which play a dominant role in processes of heat and mass transfer in protective clothing systems, is still a big challenge for researchers. The problems can be analyzed through theoretical models, experimental studies and numerical simulations. During last years, computer power has increased significantly, allowing for the numerical simulation of increasingly complex applications. In this paper, we apply **C**omputational **F**luid **D**ynamics to protective clothing modeling. Numerical studies were performed for better understanding of air penetration through the clothing – body part system.

We considered a 2-dimensional cylindrical body, covered by a porous medium, placed in a uniform turbulent air flow. This is the simplest model of human body part (e.g. an arm) covered by a protective clothing. Figure 1 shows schematically the problem formulation. We have considered the body part as a solid cylinder, and protective garment as a porous layer, characterized by a given air permeability. The space between the clothing material and the body part is filled with air. We considered steady state flow situations only (no changes of mean flow properties in the time, no movement of the body part).

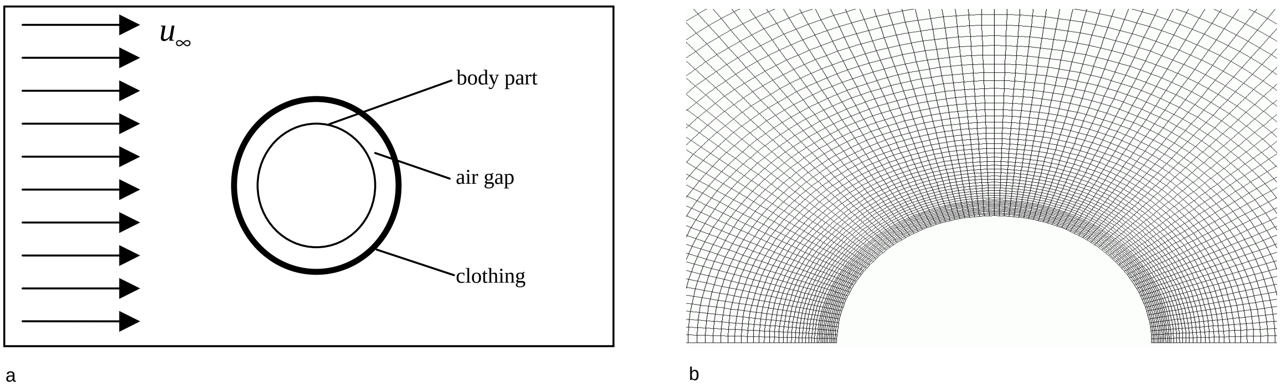

Figure 1. *Schematic problem formulation (a) and a small part of computational domain with mesh (b)*

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NOMENCLATURE

Roman letters

c	mass fraction
c_p	specific heat, J/kg/K
Da	Darcy number, see Table 1
Da_s	Damköhler number, see Table 1
D	diffusivity, m²/s
I_c	porous thickness ratio
I_g	air gap thickness ratio
K	permeability of the porous medium, m²
L	characteristic length
Nu	Nusselt number, see Table 1
Pr	Prandtl number, see Table 1
P	pressure, Pa
Re	Reynolds number, see Table 1
Sc	Schmidt number, see Table 1
Sh	Sherwood number, see Table 1
$\boldsymbol{S}$	source term vector, Pa/m
T	temperature, °C
u_∞	free stream velocity, m/s
$\overline{V}$	mean velocity component, m/s
v'	fluctuating velocity component, m/s
$\boldsymbol{V}$	velocity vector, m/s

Greek letters

α	binary parameter
δ_c	porous medium thickness, m
δ_g	air gap thickness, m
λ	thermal conductivity, W/mK
μ	viscosity, Pa·s
ρ	density, kg/m³

Subscript

∞	free stream
c	cloth
g	air gap

COMPUTATIONAL DETAILS

The fluid flow around blunt bodies is described by a set of differential equations: the continuity equation and the *Navier-Stokes* or momentum balance equation [7]. In general the mass conservation (continuity) equation is given by formula:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{V}) = 0 \tag{1}$$

for steady state ($\partial / \partial t = 0$) and incompressible flow ($\rho = const.$) we can write:

$$\nabla \cdot \boldsymbol{V} = 0 \tag{2}$$

The momentum equation for steady state and incompressible flow is given by:

$$\rho \nabla \cdot (\boldsymbol{V}\boldsymbol{V}) = -\nabla P + \nabla \cdot \overline{\overline{\tau}} + \alpha \boldsymbol{S} \tag{3}$$

where α is a binary parameter:

$$\alpha = \begin{cases} 1 & \text{in the porous region} \\ 0 & \text{in the fluid region} \end{cases}$$

$\overline{\overline{\tau}}$ denotes the viscous stresses tensor, given by:

$$\overline{\overline{\tau}} = \mu \left(\nabla \boldsymbol{V} + (\nabla \boldsymbol{V})^T \right) \tag{4}$$

and $(\cdot)^T$ denotes a transposed vector. The momentum source term in the porous region is equal to the pressure gradient in the porous medium in accordance to the Darcy equation:

$$\boldsymbol{S} = \frac{\mu}{K} \boldsymbol{V} . \tag{5}$$

The heat transfer equation for the considered system may be written as:

$$\rho c_p(\boldsymbol{V}\ \nabla)T = \lambda\nabla^2 T \qquad (6)$$

and in a similar way the species transport equation for a gas that is present in the air in small concentrations

$$(\boldsymbol{V}\ \nabla)c = D\nabla^2 c\ . \qquad (7)$$

Here it is assumed, that heat and mass transfer through the clothing is mainly convective, and solid heat conduction and mass diffusion in the clothing fiber material is neglected.

The above equations have been presented in dimensional form. In order to reduce the number of parameters describing the problem, it is more useful to make the equations dimensionless by scaling the variables with a reference value. As a result, dimensionless parameters appear in the equations, describing the problem has been presented (see Table 1).

Dimensionless group	**Definition**
Reynolds number (Re)	$\frac{\rho u_\infty L}{\mu}$
Darcy number (Da)	$\frac{K}{\delta_c^2}$
Damköhler number (Da_s)	$\frac{k_r \delta_g}{D}$
Prandtl number (Pr)	$\frac{\mu c_p}{\lambda}$
Schmidt number (Sc)	$\frac{\mu}{\rho D}$
porous thickness ratio (I_c)	$\frac{\delta_c}{L}$
air gap thickness ratio (I_g)	$\frac{\delta_g}{L}$

Table 1. *The set of dimensionless parameters used for describing the discussed problem*

Assuming constant air properties, we can make above equations dimensionless by introducing the following dimensionless parameters:

$$\hat{\boldsymbol{V}} = \frac{\boldsymbol{V}}{u_\infty} \qquad \hat{c} = \frac{c}{c_\infty} \qquad \hat{T} = \frac{T - T_\infty}{T_S - T_\infty} \qquad \hat{P} = \frac{P}{\rho_{ref} u_\infty^2} \qquad \hat{\nabla} = \nabla L \qquad (8)$$

where u_∞ is the free stream velocity, c_∞ is the free stream concentration of the trace gas, T_∞ is the free stream air temperature, T_s is the surface temperature of the inner cylinder, and L is the characteristic length taken here as the outer cylinder diameter. This leads to dimensionless equations as below:

1. Continuity equation:

$$\nabla \cdot \hat{\boldsymbol{V}} = 0 \qquad (9)$$

2. Momentum equation:

$$\nabla \cdot \left(\hat{\boldsymbol{V}}\hat{\boldsymbol{V}}\right) = -\hat{\nabla}\hat{P} + \frac{1}{Re}\hat{\nabla} \cdot \left[\hat{\nabla}\hat{\boldsymbol{V}} + \left(\hat{\nabla}\hat{\boldsymbol{V}}\right)^T\right] + \alpha\frac{I_c^2}{Da\,Re}\hat{\boldsymbol{V}} \qquad (10)$$

3. Heat transfer equation:

$$\left(\hat{\boldsymbol{V}}\ \hat{\nabla}\right)\hat{T} = -\frac{1}{Re\,Pr}\hat{\nabla}^2\hat{T} \qquad (11)$$

4. Species transport equation:

$$\left(\hat{\boldsymbol{V}}\ \hat{\nabla}\right)\hat{c} = -\frac{1}{Re\,Sc}\hat{\nabla}^2\hat{c} \qquad (12)$$

The computational domain consists of three parts: the external air flow, the porous medium and the air gap between the body part and porous cylinder. The outer flow has been considered as a turbulent. The porous medium has been treated by adding a momentum sink, in accordance with Darcy's law, to the momentum equation (10). The flow in the air gap has been treated as laminar because the highest value of Reynolds number based on air gap width was $5 \cdot 10^2$.

For the outer, turbulent flow, we used **RANS** ("*Reynolds Averaged" Navier-Sokes*) approach to obtain turbulence correlations that needs modeling. The instantaneous velocity vector is decomposed into a mean and a fluctuating component, viz.:

$$\boldsymbol{V} = \overline{\boldsymbol{V}} + \boldsymbol{v}' \tag{13}$$

where $\overline{\boldsymbol{V}}$ is the time averaged velocity and $\boldsymbol{v}'$ is the fluctuating component of the velocity [6]. By putting (13) into momentum equation (10), the RANS equations are obtained, which have similar general form as the instantaneous NS equation (10), with the velocity and pressure now representing time- or ensemble-averaged values. Additional terms now appear, representing turbulence effects. These so-called Reynolds stress terms have to be modeled in order to close the RANS equations. In order to model the Reynolds stresses, we used a two-equation model eddy viscosity model. Within this model, turbulence is modeled by replacing the molecular viscosity in the momentum equation by an eddy or turbulent viscosity, which is calculated from the turbulence kinetic energy (k) and turbulence dissipation rate (ε). Two additional transport equations are solved for k and ε [6].

A part of the used computational domain has been presented in Figure 1b. In order to safe computational time, we considered only the upper half of physical space (Figure 1a), based on the symmetry of the flow, using the symmetry boundary condition. In the inlet at the left hand side of the domain, a uniform horizontal velocity was specified, as well as a uniform inlet temperature and species concentration. On the surface of the inner cylinder, a no-slip boundary condition was prescribed for the velocity, as well as a uniform surface temperature. Furthermore, it was assumed that the trace gas species in the air deposits on the inner cylinder wall through a first order deposition reaction with rate $R = k_r c$. For $k_r \to 0$, this corresponds to a zero-flux Neuman boundary condition on the cylinder wall, whereas for $k_r \to \infty$, it corresponds to a $c = 0$ Dirichlet boundary condition. The other boundaries of the domain were defined as free outlets. The boundary conditions in the inlet and on the cylinder wall are listed below:

1. Inlet boundary conditions:

$$\begin{aligned}
&V_X = u_\infty \quad \rightarrow \quad \hat{V}_X = 1 \\
&V_y = 0 \quad \rightarrow \quad \hat{V}_y = 0 \\
&\boldsymbol{v}' = \frac{u_\infty}{20} \quad \rightarrow \quad \hat{\boldsymbol{v}}' = 0.05 \\
&T = T_\infty \quad \rightarrow \quad \hat{T} = 0 \\
&c = c_\infty \quad \rightarrow \quad \hat{c} = 1
\end{aligned} \tag{14}$$

2. Boundary conditions at the surface of the inner cylinder:

$$\begin{aligned}
&\boldsymbol{V} = 0 \quad \rightarrow \quad \hat{\boldsymbol{V}} = 0 \\
&T = T_S \quad \rightarrow \quad \hat{T} = 1 \\
&D\frac{\partial c}{dn} = k_r c \quad \rightarrow \quad \frac{\partial \hat{c}}{d\hat{n}} = \frac{Da_s}{I_g}
\end{aligned} \tag{15}$$

Two-dimensional computations were performed using the Fluent 5, based on the well-known pressure correction SIMPLE algorithm [3] and finite volume formulation. Second order differencing scheme has been used for all equations. As mentioned previously, two-equation turbulence model (known as k-ε) has been employed. Because of the known weakness of the standard k-ε model for cases such as the one considered here [4], the *RNG* version of k-ε has been used [5], which is known to perform better for flow around bluff bodies. The computations were performed with a standard desktop PC configuration (Intel PIII 800MHz, 192 Mb RAM).

RESULTS AND DISCUSSION

Aerodynamics results

First, the aerodynamics of the studied system has been considered. The goal of this part of the work was to study flow dependencies on the Reynolds and Darcy number. A standard case has been defined, with $Re = 7{\cdot}10^3$ and $Da = 6.6{\cdot}10^{-4}$ (for an 8 cm diameter inner cylinder and a cloth thickness of 0.5 mm, this corresponds to a free air velocity $u_\infty = 1.3$ m/s, and a cloth permeability $K = 0.16{\cdot}10^{-9}$ m^2, the latter leads to an air resistance of 15 Pa/(m/s)). In all cases I_c was $5{\cdot}10^{-3}$, I_c was $5{\cdot}10^{-2}$, Pr was 0.7 and Sc was 1.2. All of the described cases were in the subcritical flow regime, the highest Reynolds number being Re=$35{\cdot}10^3$ [1].

Figure 2a presents the streamline distribution for the standard case. Analyzing this graph we can distinguish two regions in the air gap between the body part and the clothing material: The upstream region, where air flows through the clothing into the air gap, and a second region, where air flows out again. In order to see where the border between these two regions is, we can analyze Figure 2b. This graph presents the pressure coefficient distribution for the surface of the outer and inner cylinder, as a function of the angle Θ, measured from the upstream stagnation point. From $\Theta = 0°$ up to about $\Theta = 52°$, the pressure outside the clothing is higher than inside. This is the region where air flows through the clothing into the air gap. For $\Theta > 52°$, the pressure outside is lower than pressure inside the air gap, and air flows out. The outer pressure distribution is almost identical to known results for a single solid cylinder, as reported by different investigators in experimental work [2]. The shape of outer pressure distribution curve also proofs the subcritical character of the flow [1], [9].

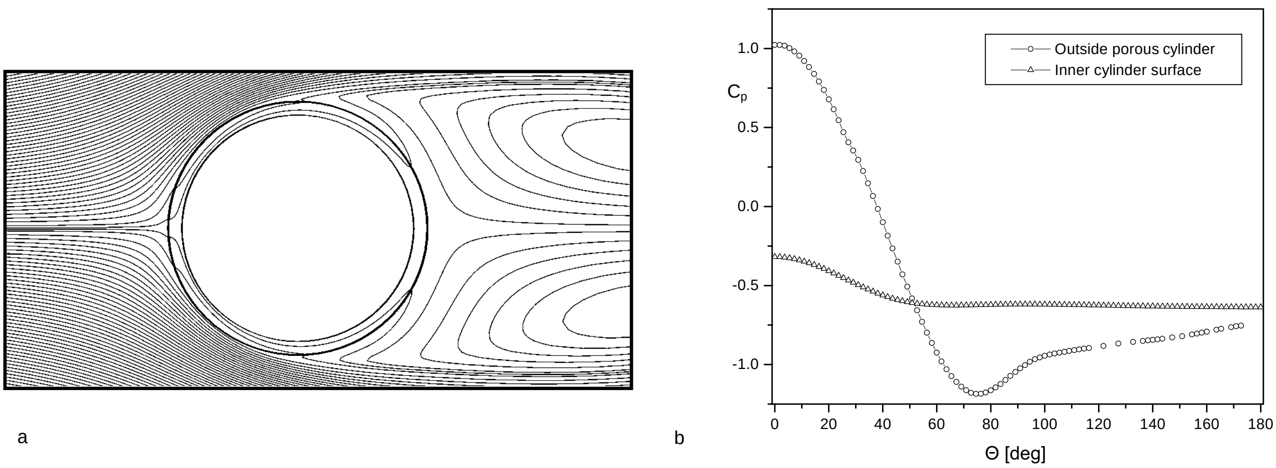

Figure 2. *Stream lines (a) and pressure coefficient distribution (b) for typical case*

Figures 3a and 3b present the tangential velocity component inside the air gap, averaged across the air gap height, as a function of angle. For the ease of comparison, the computed velocities have been normalized with free stream velocity.

In Figure 3a, normalized averaged tangential velocities have been displayed for different values of Darcy number and a fixed Reynolds number $Re = 7{\cdot}10^3$. For higher value of Darcy number, and consequently for higher permeability, the normalized air velocities inside the air gap are higher. The normalized velocity depends approximately linear on the Darcy number.

Figure 3b presents the normalized averaged tangential velocity component for fixed Darcy number $Da = 6.6{\cdot}10^{-4}$ and different values of the Reynolds number. For higher value of the Reynolds number, and consequently for higher air velocities, the normalized air velocities inside the air gap are higher. The dependence of the normalized velocity on the Reynolds number is again approximately linear.

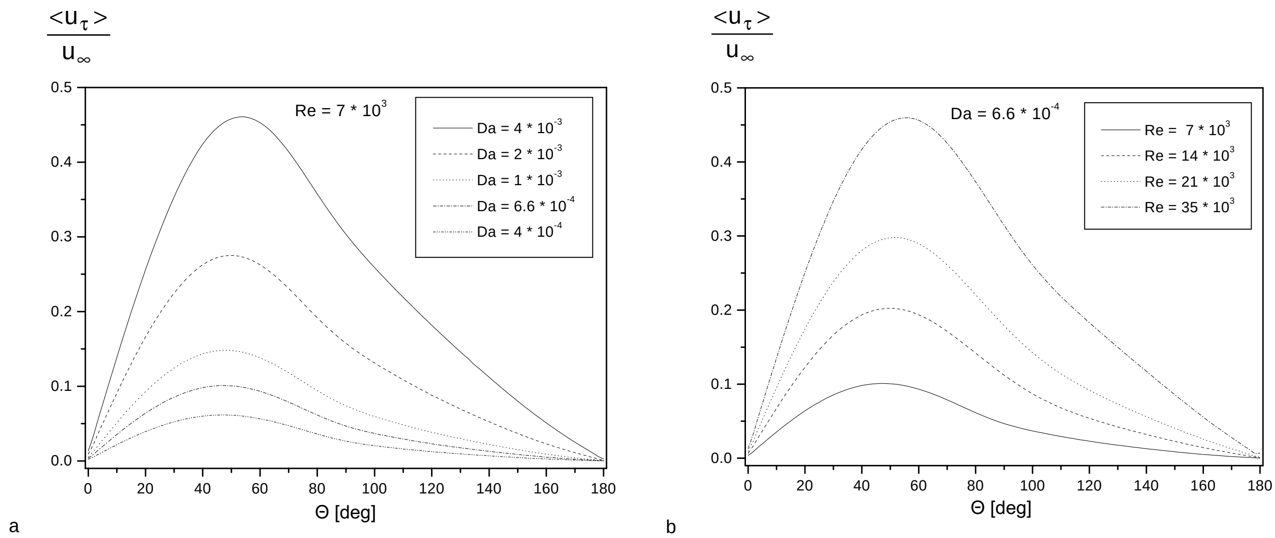

Figure 3. *Averaged tangential velocity component inside air gap as a function of angle for different Darcy (a) and Reynolds (b) number*

The observed behavior, i.e. the similar dependence of the normalized velocities in the air gap on the Darcy and the Reynolds number, can be explained from their similar appearance in the momentum sink term in the Navier-Stokes equation (10):

$$\hat{S} = \frac{I_c^2}{Da\,Re}\hat{\mu}\hat{\boldsymbol{V}} \tag{16}$$

For the considered problem we have: $\hat{\mu} = const$ and $I_c^2 = const$, which implies:

$$\hat{\boldsymbol{V}} \sim Da\,Re\,. \tag{17}$$

It should be noticed, that the Reynolds number is based on the diameter of the outer cylinder, whereas the Darcy number is based on the porous material thickness.

Heat and mass transfer results

The heat transfer to the inner cylinder (body part) has been computed for three different values of the Darcy and Reynolds number. Results are presented in Figure 4a, b and c, each of which presents six different curves for given Reynolds number $Re = 7{\cdot}10^3$, $14{\cdot}10^3$ and $35{\cdot}10^3$, respectively. The first group of displayed quantities is the dimensionless air temperature $\langle T \rangle$, averaged over the height of the air gap (left axis). The second group gives the distribution of the local Nusselt number Nu (right axis). Both of them are presented for three values of the Darcy number, $Da = 4{\cdot}10^{-4}$, $6.6{\cdot}10^{-4}$ and $10{\cdot}10^{-4}$, respectively.

For the lowest value of the Reynolds number, the temperature distribution has a maximum around $\Theta = 100 - 120°$. For higher Darcy number, the maximum becomes smoother and shifts to larger angles. In Figure 4b, at a higher Reynolds number, we can observe similar behavior, but the temperature distribution becomes smoother and the maximum is located at larger angles. Comparable results have been found in [8]. The last picture, at the highest Reynolds number, shows a bit different behavior: for the lowest value of Darcy we can observe a smooth shape of the temperature distribution, but no maximum is present. For the higher Darcy numbers, the temperature curve has again a maximum. It appears because the flow inside the air gap changes, exhibiting a separation point and a recirculation zone. For every graph we can notice that the most efficient cooling occurs at locations where outer air enters the air gap (see Figure 2a and b). Analyzing the local Nusselt number distribution in figures 4a, b and c, we can observe exactly the same dependencies on the Darcy and Reynolds number. The highest value of Nusselt number responds to the highest heat flux and in consequence to the most efficient cooling.

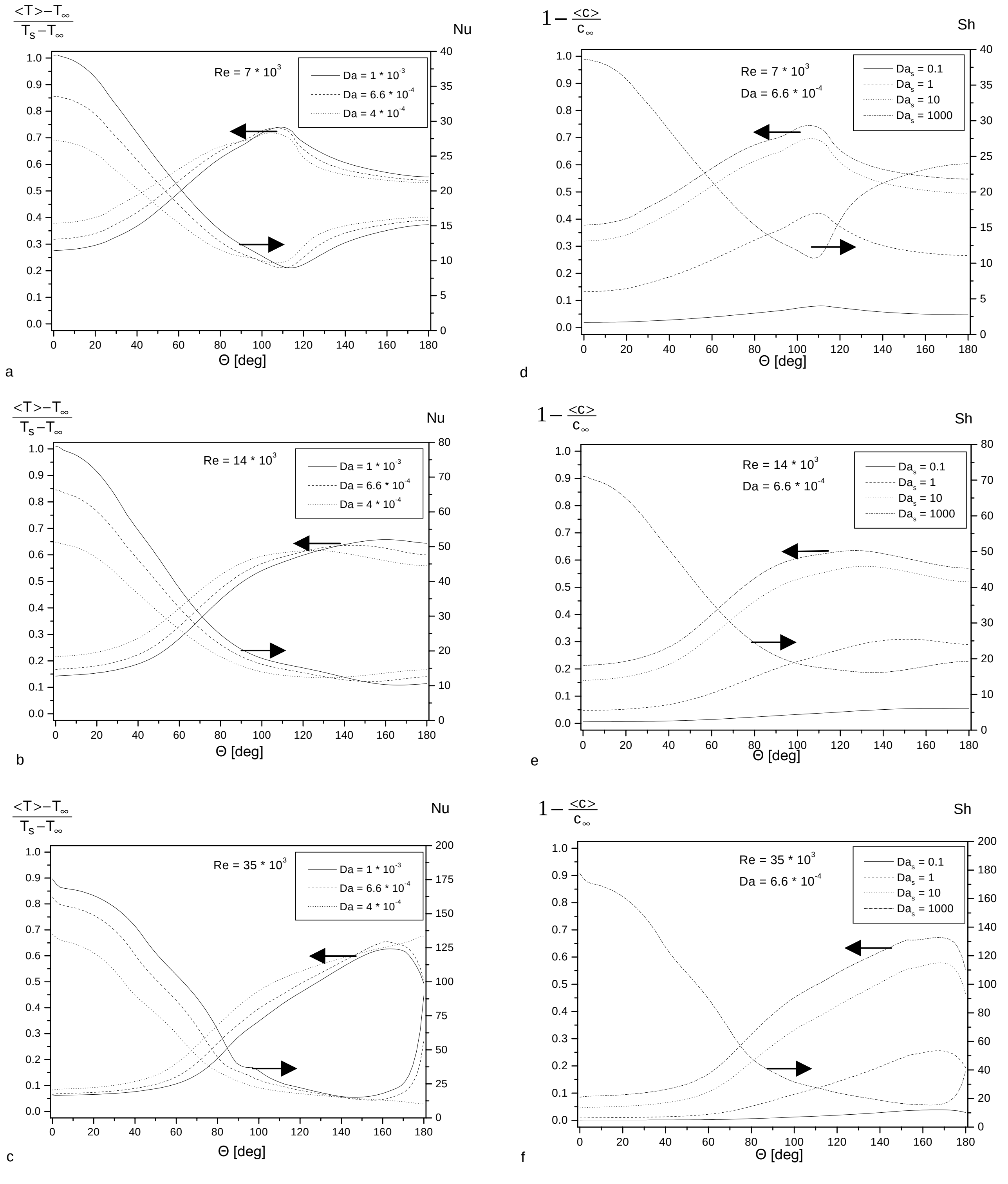

Figure 4. *Averaged relative temperature inside air gap and local Nusselt number (a, b, c) as a function of angle for different Darcy number and averaged relative mass fraction inside air gap and local Sherwood number (d, e, f) as a function of angle for different Damköhler number*

Mass transfer has been computed for the same three different Reynolds numbers, and a fixed Darcy number $Da = 6.6 \cdot 10^{-4}$. For these calculations, a trace gas (mass fraction 1%) was added to the air flow. It was assumed that the physical properties of the air and trace gas mixture were equal to those of air. On the surface of the inner cylinder, the trace gas is absorbed according to a first order reaction. The surface reaction rate is related to the Damköhler number. In Figure 4d, e and f, the dimensionless trace gas mass fraction profiles, again averaged over the height of the air gap, are presented for different surface reaction rate (left

axis). The lowest value of Damköhler number corresponds to the lowest surface reaction rate, meaning that most of the transported gas is not absorbed on the inner cylinder surface. It is easy to observe the influence of reaction rate on the mass fraction distribution. For low values of Damköhler number there is almost no difference between the free stream concentration and the concentration in the air gap between clothing and body part. When the reaction rate increases, the concentration inside the air gap becomes smaller than the free stream concentration, up to the extreme case when $Da_s \to \infty$ and the surface concentration is almost zero. The highest presented value of Damköhler number is $Da_s = 1000$, because the differences of averaged concentration profiles for higher Da_s are negligible. For large values of Da_s (corresponding to a Dirichlet boundary condition $c = 0$ at the inner cylinder surface), the dependency of the mass fraction distribution on the Reynolds number is very similar to the previously described dependency of the temperature distribution: for the lowest value of the Reynolds number, the concentration profile has a clear maximum. For the next higher Reynolds number (Figure 4e), the mass fraction curve has a smoother shape and the extreme value occurs at larger angle. At the highest Reynolds number, the influence of flow separation inside the air gap can again be observed. As is to be expected, for large values of Da_s, the Sherwood number for mass transfer to the inner cylinder is almost identical to the Nusselt number for heat transfer. Small differences being due to the fact that the Prandtl number for heat diffusion ($Pr = 0.7$) is not exactly equal to the Schmidt number for mass diffusion ($Sc = 1.2$).

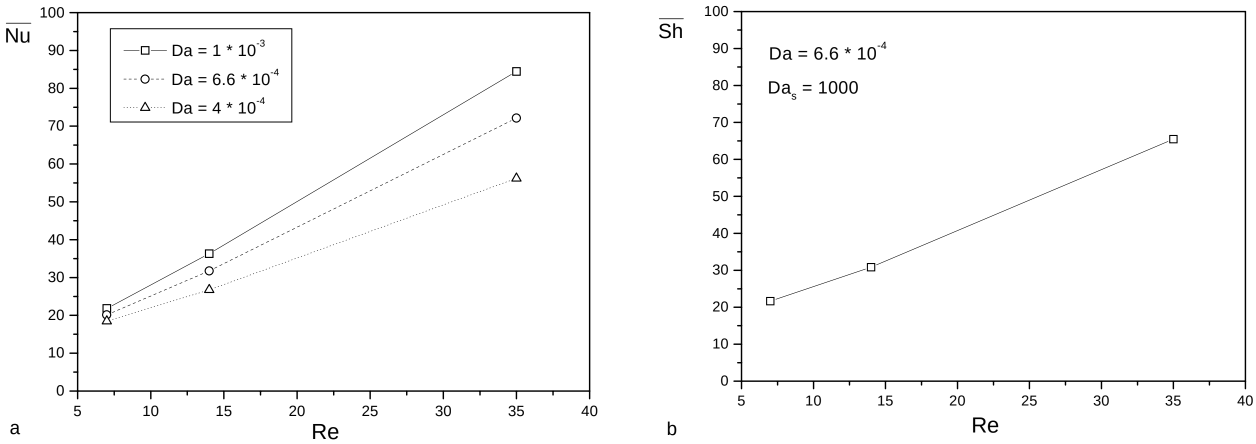

Figure 5. *Averaged Nusselt (a) and Sherwood number for large Damköhler number (b) as a function of Reynolds number*

Figure 5 presents the Nusselt and Sherwood number (for large Da_s), averaged over the entire surface of the inner cylinder, as a function of Reynolds number (based on the outer cylinder diameter). For the same value of the Darcy number, heat and mass transfer are almost identical, as expected. Surprising is the linear dependence of Nu and Sh on Re. This can be understood as follows: Based on well-know correlations for the heat transfer of a long cylinder, the Nusselt number can be written as

$$Nu \sim \left(\frac{< v_\tau > \delta_c \rho}{\mu} \right)^{\frac{1}{2}} \cdot Pr^{\frac{1}{3}} \tag{18}$$

From our analysis we found, that

$$\frac{< v_\tau >}{u_\infty} \sim Re \tag{19}$$

Combining these two equations, we find (for fixed ρ, μ and δ_c)

$$Nu \sim Re \cdot Pr^{\frac{1}{3}} . \tag{20}$$

A similar analysis can be given for the Sherwood number. This explains the linear dependence of the Nusselt and Sherwood number on the Reynolds number. For higher values of Reynolds, heat and mass transfer become more intensive.

CONCLUSIONS

In this paper, the dependency of air flow and heat and mass transfer through protective clothing around a cylindrical body part was studied as a function of the external flow velocity and the clothing material permeability. All results have been presented in dimensionless form, making them more generally applicable. One of the most important conclusions is that the air flow enters through the clothing material for angles up to $50-60°$ (measured from the stagnation point) only. This gives a general impression on locations, which are sufficiently ventilated, the others which are more endangered by poisonous gases in the air. The heat and mass transfer results accurately confirm the noticed effect; the lowest values of temperatures and highest for concentration appear for angles up to $50-60°$. For the same angle range, a maximal value of Nusselt and Sherwood numbers occurs, indicating large heat and mass transfer for this region.

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Thermal Protection Against Hot Steam Stress

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Summary
In order to answer to the needs of the French Navy, the thermal protective capacities of textile samples and protective garments are assessed under hot steam stress with a testing device developed in our institute. In a first series, textile samples are exposed to three conditions of hot steam jet (leading to three rates of heat flux: 4.31, 3.39, and 2.80 $W.cm^{-2}$) and to a hot saturated environment (80°C and 100% of relative humidity leading to a heat flux of 0.70 $W.cm^{-2}$). In a second series, protective garments are tested in a hot saturated environment (80°C and 100% of relative humidity) on a thermal manikin.
With the same thickness or inferior one, the textile samples and garments impermeable to water vapour are more efficient to limit the heat transfer due to hot steam stress exposure than the permeable ones. Moreover, thicker is the sample or the garment, higher is the thermal protection it gives. But, there is a maximal thickness over which the gain of protection is not enough sufficient to justify the increase of thickness. The diffusion of the water vapour through the textile samples and its absorption bring additional heat and decrease the protective capacities of the textile fabrics. This mechanism is observed with the permeable samples at the beginning of the exposure to hot steam jets and should be take into account to evaluate the samples or the garments to avoid skin burn. This mechanism is also observed with one impermeable sample after a time delay of exposure (depending on the steam conditions and the textile) probably due to a denaturation of the impermeability of the sample.
In conclusion, the best protection against hot water steam stress should be given by a thick, multi-layered and impermeable to water vapour garment with a wide cut to limit the contact with the skin.

Introduction
Accidental exposure to hot water steam is a potential hazard in the French Navy and particularly on nuclear submarines or ships. Exposure to hot steam atmosphere leads to severe and sometimes letal injuries in respiratory airways (Hathaway et al., 1996; Moritz et al., 1945) or in skin (Still et al., 2001).
In order to protect the submarine crew members of the French Navy, a study is carried out on protective capacities of textiles and equipments under hot steam stresses. A « steam laboratory » was created at the Institut de Médecine Navale du Service de Santé des Armées. A set of tools was developped: (i) a testing device for textile samples evaluation, (ii) a thermal manikin and a climatic chamber for clothings and procedures evaluation under steam stresses.

Materials and methods
Serie 1.
The device for textile sample evaluation can be used under two configurations: steam jet or steam atmosphere. It is composed of a steam generator (Sano clav Wolf, Bioblock, France), a sample support, a measuring cell (composed with a heat flux sensor, Episensor 025, JBMEurope, France) in which water circulates at a regulated temperature of 33°C, and a data logger (DaqBook 216, IOtech, USA) and a computer that allows to observe and save the measures (software: Daqview 7.1, IOtech, USA). Under steam jet configuration, the sample support and the measuring cell are fixed on a moving base. Under steam atmosphere configuration, this moving base is replaced by an isolated box in which steam atmosphere is created. In this configuration, the steam injection is made by an electrovalve asserved to a thermal regulator which regulates the box temperature at 80°C.

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

Table 1 shows the caracteristics of the basal samples which are presented in this paper.
The protocol is the same for all the conditions and corresponds to 10-min exposure to steam stress: the 3 jet conditions (J5, J10 and J15) depending on the distance between the steam output of the generator and the external side of the samples (respectively 5, 10 and 15 cm) and the atmosphere condition (ATM). The reference tests (REF) correspond to the measuring cell directly exposed to the steam stresses (4.312 ± 0.026, 3.394 ± 0.039, 2.804 ± 0.033 and 0.702 ± 0.117 $W.cm^{-2}$ for respectively J5, J10, J15 and ATM). Each test (REF or samples) is repeated 3 times.
The heat flux is measured every second throughout the exposure. The following variables are calculated with the heat flux values. SMF (Steam Mean Flux, $W.cm^{-2}$) corresponds to the average of the heat flux of 3 tests over the last minute of the exposure. AHT (total Amount of Heat Transfered, $J.cm^{-2}$) corresponds to the cumul of the heat transfered to the cell over the 10-min exposure. PR (Percent of REF, %) corresponds to the ratio between the SMF of the sample and those of the corresponding REF.
The results for three textiles samples, described in Table 1, are presented in this paper.

	Thickness (mm)	$\mathbf{R_T}$ ($m^2.K.W^{-1}$)	$\mathbf{R_e}$ ($m^2.Pa.W^{-1}$)
TC	0.50	0.0252	4.3
TX	0.40	0.0121	398
TLD	0.25	0.0198	10000

TABLE 1: Caracteristics of the samples. R_T: thermal resistance. R_e: evaporative resistance (EN 31092).

Serie 2.
Five protective equipments are evaluated on a copper thermal manikin in a 80°C saturated environment. The thermal manikin is divided in nine separate segments. The surface temperature is regulated at 33°C by water circulating inside copper pipes which are distributed on the internal face of the sheets (regulated surface: 1.349 m^2). The water flows are measured (Mc Milan Co, USA) and regulated at the output of each segment between 0.06 to 1.00 $l.m^{-1}$ (± 5%). Thus, total and local heat fluxes are calculated from temperatures and water flows. The REF test correspond to the nude manikin exposed to the climatic conditions. During the equipment tests, the thermal manikin is worn with the equipment and placed in the center of the chamber. For all the tests, the climatic conditions are 80°C of air temperature with step increase of humidity to the maximum allowed by the equipment. Due to high level of condensation on the regulated surface of the manikin, the chamber cannot reach saturation when the manikin is in. Thus, humidity is increase by step to the maximum the chamber can reach. And the heat flux value at saturation is extrapolated by exponential regression. For each step, the mean temperature of the surface of each segment of the manikin is regulated at 33°C. Temperatures and water flows are measured for each step over 7 minutes. Local and total heat fluxes are then calculated for each step. And the heat fluxes for saturation are calculated by extrapolation. The equipments are classified depending on their heat fluxes.
We present the results for five garments: TLD, TC, TBoy, TVTN and TMat. TLD and TBoy are water vapour impermeable garments. TC, TVTN and TMat are water vapour permeable ones. TC, TVTN and TLD are thin garments, while TBoy and TMat are thick ones. All these garments cover all the manikin surface except the head. The comparison between garments is made with the heat fluxes measured on the surface covered.

Results
Serie 1.
The Figure 1 shows some typical exemples of heat flux pattern during the 10-min exposure to the J10 condition. During REF tests (curve 1), the heat flux increases rapidely (in 2 to 3 sec) to a steam steady state (SMF = 3.394 ± 0.039 $W.cm^{-2}$). During TC tests (curve 2), there is a peak of the heat flux at the beginning of exposure. Then after, heat flux decreases to finally stabilise at a new level maintened till the end of the exposure (SMF = 1.606 ± 0.031 $W.cm^{-2}$). During TX tests (curve 3), the heat flux reaches rapidely a first steam steady state. But, after about 140 sec, the flux increases again till the end of exposure. During TLD tests (curve 4), the heat flux reaches rapidely the steam steady state (SMF = 0.808 ± 0.024 $W.cm^{-2}$).

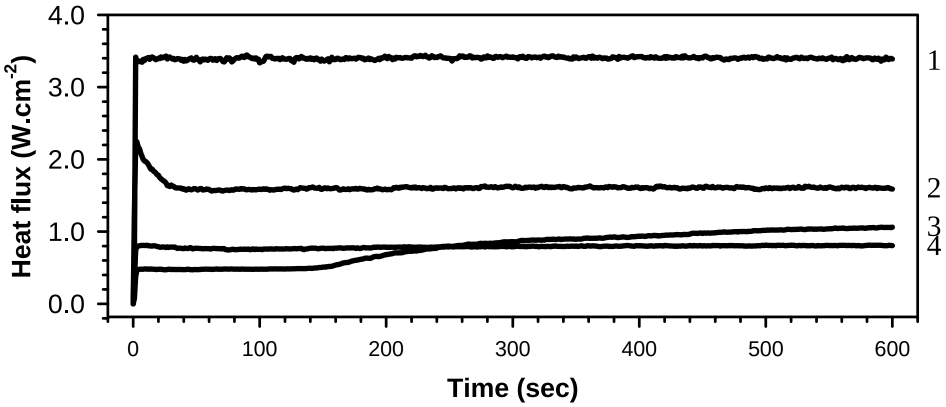

FIGURE 1 : Typical patterns of heat flux observed during the 10-min exposure to J10 condition (see text).

Figure 2 shows the impact of two ways of impermeabilization of a textile sample (TC) on the heat flux pattern during J10 condition. The impermeabilization is made either in adding a polyethylene foil of 10 µm thickness (P) ahead of TC (P+TC) and behind TC (TC+P) or in soaking TC just before the tests (TCm). When P is placed ahead of TC (P+TC), the pattern is typically those of an impermeable fabrics. But, when P is placed behind of TC (TC+P), the pattern is the same as TC alone but the peak is significantly decreased and SMF is lower. When TC is soaked before the tests (TCm), the peak is also significantly decreased and SMF is the same as TC.

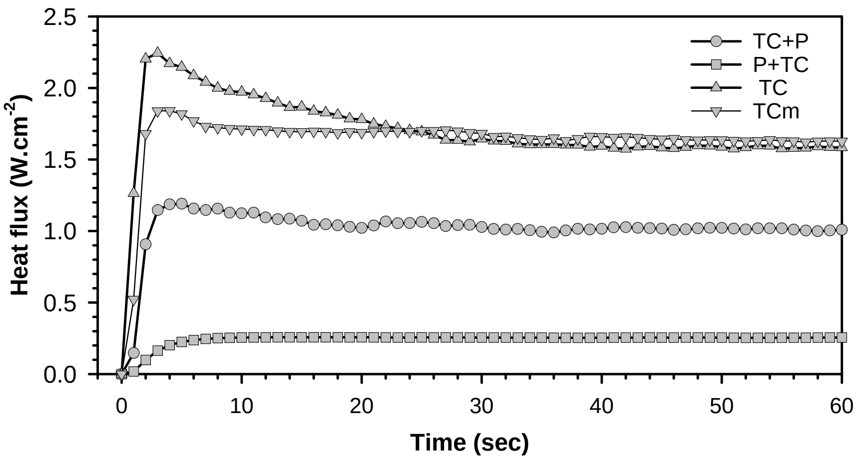

FIGURE 2: Heat flux of samples composed with TC during the first minute of exposure to J10 condition.

Table 2 shows the main results observed in condition J10 when the air layer behind the fabrics (TC and TLD) is increased artificially in adding one (3D4) or two layers (3D8) of a 3D polyethylene waffle fabrics of 4 mm thickness. Increasing the thickness of the air layer behind fabrics leads to lower SMF, AHT and PR, whatever the permeability of the fabrics. For the same thickness or a lower one, the impermeable fabrics leads to lower levels.

Sample	**SMF** (W.cm^{-2})		**AHT** (J.cm^{-2})		**PR** (%)	
REF	3.394	(0.039)	2038.2	(26.4)	-	
TC	1.606	(0.031)	968.8	(6.2)	46.5	(1.3)
TC+3D4	0.591	(0.017)	381.5	(7.1)	17.4	(0.7)
TC+3D8	0.388	(0.005)	249.9	(4.3)	11.8	(0.3)
TLD	0.808	(0.024)	473.3	(22.0)	23.7	(1.0)
TLD+3D4	0.069	(0.001)	41.3	(1.2)	2.0	(0.0)
TLD+3D8	0.042	(0.000)	24.6	(0.0)	1.3	(0.0)

TABLE 2: Main results observed in increasing the thickness of the air layer behind fabrics in condition J10.

SMF: steam mean heat flux. AHT: amount of heat transferred to cell in 10 minutes. PR: percent of the REF heat flux transferred.

Figure 3 shows the pattern of the heat flux observed with TX during the 3 conditions of steam jet. After a first increase at the beginning of exposure to steam, the heat flux increases again after a delay of steady state. The delay before increase and the range of increase depend on the condition.

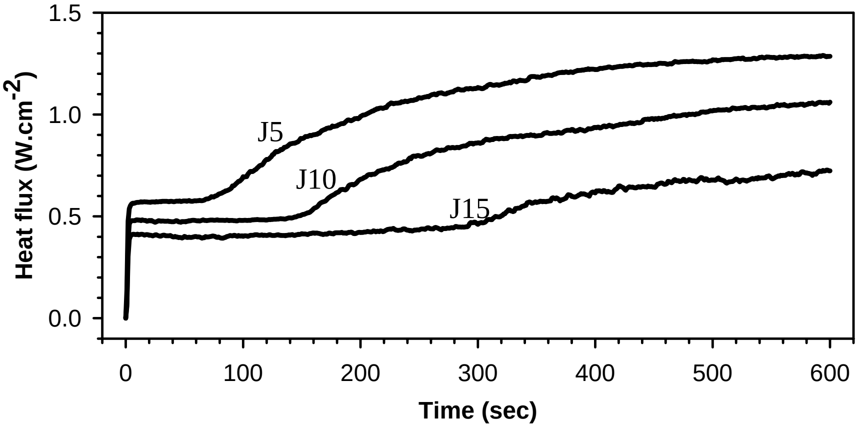

FIGURE 3: Heat flux observed with TX during the 3 conditions of steam jets.

Serie 2.
Figure 4 shows the local and total ratios between the mean heat flux of the samples and these of the REF test (PR, %). In a general way, results observed on garments and fabrics have the same meaning. The permeable garments to water vapour TC and TVTN lead to higher levels of heat flux and PR, since these 2 garments are thin. But TMat lead to about the same level of PR than TLD due to the higher thickness of the textile fabrics, composed with different textile layers. The best protection is brought by TBoy, TLD and TMat, and the lowest one by TC. The figure shows also that there is a higher difference between the local ratios with permeable garments, and specially between limbs and the others body segments.

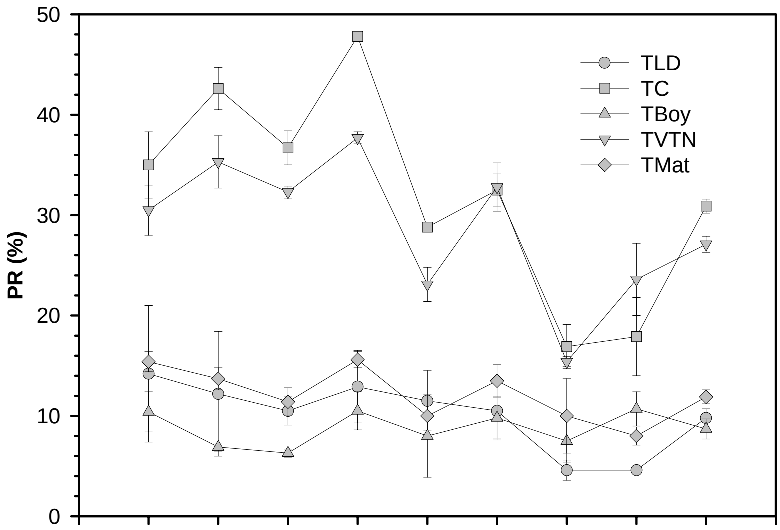

FIGURE 4: Ratio between the heat flux of the garments and those of the REF. TAv: front of the trunk, TAr: back, BG and BD: left and right arms, CG and CD: left and right thighs, MG and MD: left and right legs, Tot: total.

Discussion
In a general manner, the tests on textile fabrics and on garments are in good agreement. With the same thickness or inferior one, the textile samples impermeable to hot water steam are more efficient to limit heat transfer due to exposure to hot water steam than the permeable ones. At the beginning of the steam jet exposure, the permeable samples show a peak of the heat flux measured probably due to complex

phenomenons of condensation, diffusion and absorption of water inside sample releasing high level of heat (Farnworth, 1986; Lotens and Havenith, 1994). The « impermeabilisation » of permeable sample leads to the loss of these phenomenons. These phenomenons should also explain the results observed with TX (impermeable sample). After a delay of steam jet exposure, the sample seems to change its characteristics, and progressively becoming permeable. In this case, while the denaturation is not instantaneous, no peak of heat flux is observed but rather a regular increase depending on the denaturation rapidity. The rapidity depends on the level of steam agression. The denaturation is reversible for this sample. The maintenance of the properties of the textile samples should be evaluated under steam aggression to avoid skin injuries.
Moreover, thicker is the sample, higher is the thermal protection it gives. But, it seems to exist a maximal thickness over which the gain of protection is not enough sufficient to justify the supplementary increase of thickness.
In the same way, impermeable garments are more efficient to protect under steam stress. Furthermore, a loose-fitting cut (with a thick air layer between the garment and the skin) allows to increase the level of thermal protection of a thin garment. The ergonomic consequences of this kind of protection for human tolerance to work are to be evaluated.

Conclusions

The best protection against hot water steam aggression should be given by a thick, multi-layered and impermeable to water vapour garment with a wide cut to limit touches with skin. Moreover, the equipment should covered all the body surface to protect the skin surface and also the respiratory airways and the eyes. In these conditions, this protective garment should not be worn continually. The study should be continue to find a solution to protect the submarine crew members during their daily work.

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Fire Fighter Garment with Non Textile Insulation

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Summary

A waterproof barrier combined with heat stable „spacers“ creates the thermal insulating air buffer.Fire fighting suits with the new insulation system fullfill thermal protection according EN 366 and EN 367 and are successfull in thermo-man test of DuPont. A controlled wear trial in a climatic chamber showed a higher physiological performance of the new system compared to traditional ones (GORE-TEX® and leather with non woven insulation).

Introduction

Fibers and yarns are not the real thermal insulater of a garment. It is the locked still standing air. Fibers conduct the heat 10 to 20 times better than still standing air. This was the idea to substitute the traditional textile insulation by an air cushion. GORE-TEX®Airlock® is a combination of moisture barrier and thermal protection: Heat stable „spacers“ of foamed silicone on the GORE-TEX® moisture barrier create the insulating air buffer.

Hot plate measurements showed that at similar heat resistance we gained a 40% lower water vapor resistance with the new system whereas the water vapor absorption was reduced by 60%.Transient measurements showed that the Airlock® system features a higher transportation rate but lower absorption rate for liquid water.Consequently a combination with Airlock® causes a significantly shorter drying time.
Conclusion out of this physical data : For wear situations with strong sweating,as experienced by fire fighters, a material combination with an Airlock® liner can be expected to show a better physiological performance than a material combination with a conventional textile insulation.In a controlled wear test on a treadmill in the climatic chamber we tried to proof this.

Methods

Five professional fire fighters wore the following ensembles at 30°C / 50% R.H. for 95 min:

- Leather jacket with lining but without moisture barrier,Paris style,GORE-TEX® fire fighting trousers
- Textile jacket (Nomex, Aramid lining, GORE-TEX® barrier),Berlin style,GORE-TEX® fire fighting trousers
- Textile jacket (Nomex, Airlock®, lining),Paris style, modified Airlock® fire fighting trousers

Long-legged underpants and long-sleeved undershirt of a functional material (Ullfrotte:60%wool;25%PES;15%PA)
have been worn underneath.To be close to practice each test subject wore its boots, gloves, helmet, belt and breathing apparatus (without respirator mask).
The load regimen was based on former studies and consisted of work and rest cycles:

10 min	4 km/h	0%
10 min	rest	
5 min	5 km/h	5%
10 min	rest	
5 min	5 km/h	10%
10 min	rest	
5 min	5 km/h	8%
40 min	rest	

Paper presented at the RTO HFM Symposium on “Blowing Hot and Cold: Protecting Against Climatic Extremes”, held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

Parameters measured:

Core temperature (rectal),heart rate,skin temperatures, relative humidities between underwear and suit, weight loss of subject,weight gain of clothing.At the end of each cycle,the test subjects rated their heat and moisture perception as well as the wear comfort.

Results and discussion

- Core temperature: Up to the 25th test minute, the temperature increases of the body core lay within a relatively narrow temperature band and on a comparatively low level. From that time on, however,distinct increases were observed.In the Leather fire fighting jacket, the body core temperature rose by 0.9 K, in the Berlin GORE-TEX® jacket by 0.65 K, whereas an increase of only 0.45 K was measured in the jacket Airlock®-Paris.In the Leather jacket the body core temperature was continuously rising, even after the load phase had ended (55th test minute), and kept on rising until the end of the test in the 95th test minute.In the two other jackets, the body core temperature kept gradually falling from the 75th test minute on.
- Mean skin temperature: The temperature curves lie within a band of approximately 2 to 1.3 Kelvin;Leather on the top (more than 37 °C) and Airlock®-Paris the lowest skin tempeature (nearly 36°C).Berlin GORE-TEX® was in the middle.
- Heart rates: They rose in a way which was typical for the load regimen of the test and lay within a physiologically plausible bandwidth.The small differences between the mean value curves reveal that the individual jacket types have less influence on the heart rates.It was only in the fire fighting jacket Airlock®-Paris that the heart rates returned nearly to the starting levels from the 65th test minute on.
- Weight change: The weight losses of the test persons were, on an average, approximately 1 kg in the Airlock®-Paris jacket, 1.3 kg in the Berlin GORE-TEX® jacket and 1.7 kg in the Leather jacket. The water uptake of the garment ensembles coincided with the weight losses: 0.5 kg in the Airlock®-Paris jacket; 0.7 kg in the Berlin-GORE-TEX® jacket and 1 kg in the Leather jacket.
- Relative humidity:The humidities measured in the Leather jacket ranged about 5 to 10 % above the levels measured in the two other jackets, throughout the test. It was especially in the Airlock®-Paris jacket that the humidity reached a steady state slightly above 80% r.h.
- Heat perception: It was ranked on a scale from 0 to 7 (0=comfortable; 1=slightly warm; 2=warm;3=very warm; 4=hot; 5=very hot; 6=uncomfortable;7=intolerable).Up to the end of the last walking period (55th min) the Airlock®-Paris jacket was perceived as warm to very warm; Berlin GORE-TEX® as hot and Leather as very hot.This perception continued till the end of the test, whereas the two other jackets showed an improvement.
- Moisture perception: It was ranked on a scale from 0 to 7 (0=dry; 1=chest or back slightly moist; 2=chest or back moist; 3=body moist; 4=body moist with clothing partly sticking to the body; 5=perspiration is running down at some spots; 6=perspiration is pouring down the body in many areas; 7=intolerable).Up to the end of the last walking period (55th min) Airlock®-Paris ranked 3rd and Berlin-GORE-TEX® and Leather 5th.
- Wear comfort: It was ranked on a scale from 1 to 6 (1=excellent; 2= good; 3= satisfactory; 4= uncomfortable; 5=very uncomfortable; 6=extremely uncomfortable).Throughout the test period, Airlock®-Paris was perceived as excellent; Berlin GORE-TEX® as good and Leather as very uncomfortable.

The outcome of the study was that for all parameters, except for the heart rate, a clear rank can be assigned to each jacket type tested (rank 1 = best, rank 3 = worst performance):

1. Airlock®-Paris
2. Berlin GORE-TEX®
3. Leather

Conclusions

In the fire fighting suits with the new combination of thermal protection and liquid barrier very favourable thermophysiological conditions prevailed. Such suits can be expected to produce less heat stress at the wearer. Fire fighting suits with Airlock® fullfill EN 469 and had been successfull in thermo-man-tests.With the new concept the bulkiness of insulation could be reduced while maintaining the same level of heat

protection. Due to minimal moisture absorption and high moisture vapor transfer the risk of injuries by scalding should be reduced. High flexibility and reduced weight of such suits increases the wear comfort.

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Wearing Comfort of Footwear in Hot Environments

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Dedicated to Dir. and Prof. Kunz on his 60th birthday

INTRODUCTION

The climatic wearing comfort of military footwear greatly influences the performance of the soldier. Particularly in hot and/or humid environments insufficient wearing comfort of footwear can cause severe problems. Considering that the formation of blisters can be considerably reduced if the feet are kept as dry as possible [1], means should be provided to reduce the humidity close to the surface of the foot. Even though a great diversity of so called "functional" socks and "breathable" shoes are available on the market today, there is still a lack of reliable and objective methods to simulate sweating inside the footwear at different levels of metabolic rate and to measure the resultant temperatures and relative humidities. It is, therefore, difficult to judge or compare different footwear systems (consisting of shoes, socks and inlay soles) with respect to their influence on the climatic wearing comfort.

RATIONALE

In collaboration between WIWEB and IfaErg a testing device named CYBOR (Cybernetic Body Regulation) for the simulation of climatical conditions inside a footwear system and the measurement of the resulting temperatures and relative humidities close to the foot and/or between sock and shoe has been developed. The technical specifications together with some samples of application of the device have been reported earlier [2-4]. CYBOR consists, among other, of a foot phantom, which supplies heat and moisture to the inside of footwear. The heat and moisture supply is closely related to human sweating behaviour at a given metabolic rate. An investigation has been carried out to find out about a suitable combination of socks and shoes resulting in a proposition for footwear systems to be worn in hot and hot/wet environments.

RESULTS

Five different pairs of socks with two-layer construction underneath the foot and a mixture of man made and natural fibres within the shaft have been combined with a german combat boot particularly designed for hot environments. The details of the construction of the socks are given in Tab. 1.

The temperature and relative humidity inside the foot phantom of the simulation device were set to 37 °C and 80 % relative humidity, respectively. After reaching a steady state condition (after approx. 90 min. of test duration), the temperature and relative humidity were measured in the medial area outside the foot phantom ("skin" in Fig. 1) as well as in the medial area between the sock and the shoe. Fig. 1 shows the resulting calculated water vapour pressure (wvp) values.

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Tab. 1: Construction details of socks under test and final temperatures at the end of the test as measured in the medial area.; WO = Wool, PAC = Polyacryl, PA = Polyamide, PES = Polyester (Coolmax®), PP = Polypropylene.

Sock No.	Cushion (PP)	Thickness of Shaft	Length	Fibremixture	Final temperature
1	High Volume	low	calf	WO/PAC	34,2
2	Medium Volume	low	calf	WO/PAC/PA	34,6
3	Medium Volume	low	calf	PES/PA	34,4
4	High Volume	high	calf	WO/PAC/PA	34,7
5	High Volume	high	knee	WO/PAC/PA	34,5

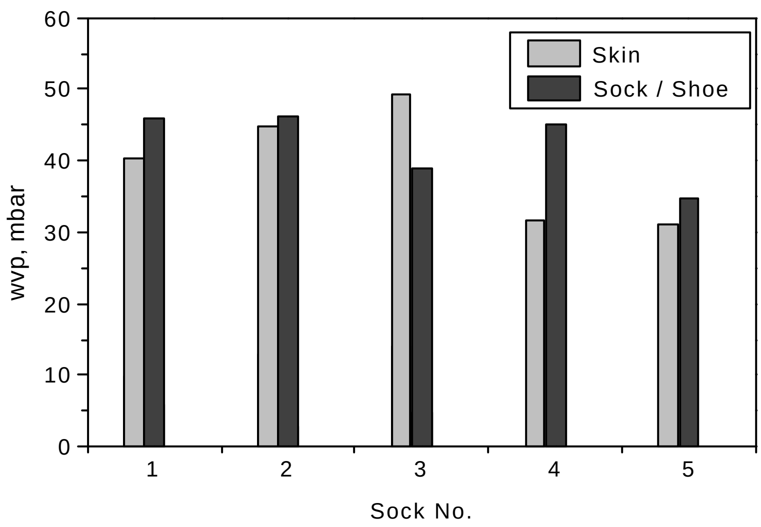

Fig. 1: Water vapour pressure (wvp) measured in the medial area inside (“skin”) and outside (“sock / shoe”) the socks under test.

Socks with thinner shafts (No. 1 - 3) tend to produce a more humid climate close to the skin even with a high volume cushion underneath the foot. The driest climate is provided by socks No. 4 and 5 with thick shaft and a high volume cushion. Sock No. 4, however, shows a comparatively high wvp-value between the sock and the shoe. The final temperatures inside all the socks under test are within a range of 0.5 °C, which means that the difference cannot be realized by the wearer. The results are interpreted as follows:

There are three different ways of moisture transport out of the shoe (Fig. 2):

1. from the skin through the sock through the material of the shaft of the shoe
2. from the skin through the sock along the inside of the shaft of the shoe
3. along the inside of the sock

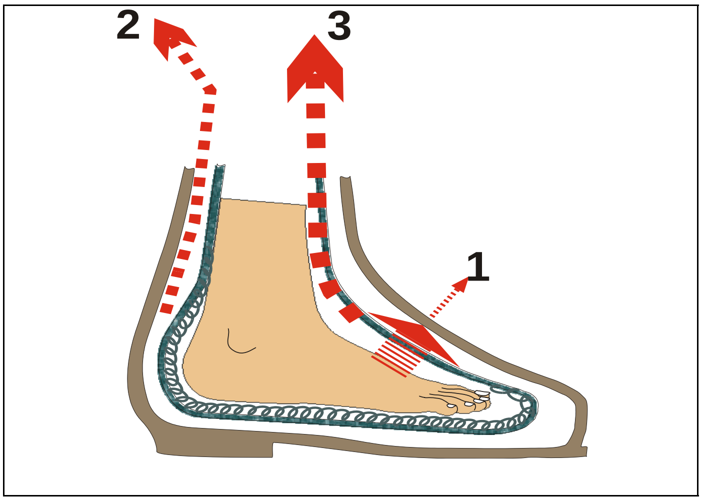

Fig. 2: Different options for moisture exchange in footwear (explanation of numbers: see text)

Option No. 1 is limited by the water vapour permeation resistance of the shoe's shaft material. Even though the shoe under test was equipped with fabric insets, the results show, that in most cases the water vapour pressure between the sock and the shoe is higher than close to the skin, which means, that the moisture transport through the shaft of the shoe is insufficient. The same applies to option 2. In case of a good fit of the shoe this transport way is blocked by a snug contact between the sock and the shoe. The most efficient way of removing moisture from the feet seems to be option 3. This can be seen from the comparatively lower "inside"wvp-values of socks 4 and 5 with thick shafts.

Two further important informations can be drawn from the results: In case of sock No. 3 the content of a high surface fibre (Coolmax®) within the shaft evidently provides a better moisture transport and a drier climate between the sock and the shoe compared to socks No. 1 and 2. No. 3, however, was the thinnest sock under test and some of the moisture loss may also be due to the loose fit between sock and shoe. The content of this particular high surface fibre in the shaft material of the sock does, however, not provide a drier climate close to the skin. In case of sock No. 4 the moisture transport option 3 may be blocked by the elastic upper end of the shaft of the sock close to the upper end of the shoe. In contrast to the knee-high sock No. 5 most of the moisture is left between the sock and the shoe, which can cause problems during longer wearing periods.

CONCLUSION

The obtained results showed, that the construction of socks have a major influence on the climatic wearing comfort of footwear systems for extreme environments. It turned out, that comparatively thicker socks will provide a drier foot climate without considerably raising the skin temperature.
Currently further tests are carried out to get more precise informations about the influence of different man made fibres with good moisture transport capabilities on the foot climate. The employed testing device CYBOR has proved to be a powerful tool for the prediction of the climatic wearing comfort of footwear systems.

The authors thank the Falke KG Company, Germany for supplying the necessary test samples.

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Testing a New Concept of Immersion Suit at Sea

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Summary

A new concept of immersion suit, the nearly dry suit, was recently developed to overcome the main limitations of the wet and dry suits. The main new feature of the suit is the adjustable seals that can be closed before or upon entry in water. The purpose of the present study was to test the new suit at sea against a standard dry suit. Seven male subjects were immersed for over one hour in 3°C water in the Atlantic ocean. Three conditions were tested during which the subjects were wearing a dry suit (DRY), a nearly dry suit with the seals closed (NEAR-DRY-C) or a nearly dry suit with the seals opened upon entry in water (NEAR-DRY-O). The thermal resistances of the suit, measured from the skin heat loss data and the temperature difference between the skin and the outside surface of the suits, were 0.95 ± 0.14, 0.69 ± 0.13 and 0.58 ± 0.09 Clo for DRY, NEAR-DRY-C and NEAR-DRY-O conditions, respectively, with the thermal resistance being significantly lower ($p \leq 0.05$) for the NEAR-DRY conditions. The decrease in insulation for the NEAR-DRY-O condition was attributed to a significantly larger water leakage through the seals (1.37 ± 0.29 L) as compared to the other conditions (DRY: 0.41 ± 0.20 L; NEAR-DRY-C: 0.35 ± 0.28 L). It was concluded that the nearly dry suit concept, while maintaining a greater comfort when the seals were opened before immersion, successfully limited the water leakage into the suit to a level observed with a dry suit when the seals were closed upon entry in water. The thermal insulation provided by the nearly dry suit when closed is not inferior to 0.75 Clo, the recommended insulation to obtain adequate thermal protection in cold water. During immersion in the open mode, the nearly dry suit can decrease the survival time by a factor a two.

Introduction

Two types of immersion suits are available today to protect aircrew against the risks associated with accidental cold water immersion, namely the wet and the dry immersion suits. The main limitation of the wet suit is its limited thermal protection during cold water immersion because of the constant leakage of water into the suit. The principal limitations of the dry suit are seal leakage, and neck and wrist seal discomfort.

A new concept of immersion suit called the nearly dry suit, was recently developed by the Canadian company Mustang Survival to overcome the main limitations of both the wet and dry suits. The main new feature of the suit is the adjustable seals that can be closed before or upon entry in water. This new feature, in addition to improve comfort, could help the aircrew to manage heat stress inside the aircraft during flight operations in temperate conditions without the assistance of an active air conditioning or cooling system. However, such a feature could also be a source of water leakage that may cause a major deterioration of the thermal properties of the immersion suit during water immersion. The consequence could be fatal to aircrew crashing in cold water because of the rapid cooling of the body and the risk of dying from hypothermia before being rescued from the water.

Purpose

The purpose of the present study was to compare the physiological responses, leakage rate, and thermal properties of the new suit concept to a standard dry immersion suit currently in use by the Canadian Forces during a simulated accidental cold water immersion in the open sea. The open sea environment was used in the present study to simulate a realistic cold water accidental immersion of aircrew at sea

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where self-rescue activities and the sea state can both influence the thermal insulation of an immersion suit.

Methods

Subjects

Seven healthy, non-smoking male volunteers with the following characteristics were recruited (mean ± S.D.): age 36.0±4.3 years, height 178.0 ± 10.0 cm, weight 80.3 ± 14.1 kg, body surface area 1.98 ± 0.20 m^2 and percentage body fat 17.6 ± 6.4%. Body surface area was calculated using the formula of Dubois and Dubois (1). Percent body fat was estimated from the skinfold from 5 body sites according to Katch et al. (2). All subjects were medically screened by a physician before being asked for their written consent. This study was approved by the Human Ethics Committee at the Defence and Civil Institute of Environmental Medicine (DCIEM).

Ambient Condition and Clothing Worn

The study was performed in the Atlantic Ocean on the Defence R&D Canada Research Ship Quest, 20 to 50 km off the coasts of Nova Scotia, Canada. The average air and water temperatures, and the average peak wave height during the study were (mean ± SD) 7.3 ± 1.0°C, 3.6 ± 0.2°C, and 2.5 ± 0.5m, respectively.

Three conditions were tested on each of the seven male subjects. In the first condition called DRY, the subjects wore a dry suit currently used by the Canadian Forces. The suit tested was the MSF750 Immersion Dry Suit by Mustang Survival that has 0.85 immersed Clo of thermal insulation as measured in stirred water on a thermal manikin (TIM; The CORD Group, NS, Canada). In the second and third conditions, the subjects wore the nearly dry suit MAC 200 also by Mustang Survival with 0.91 immersed Clo of thermal insulation as measured in stirred water on the thermal manikin. The neck and wrist seals of the MAC 200 immersion suit were closed for the second condition called NEAR-DRY-C, and opened for the third condition called NEAR-DRY-O upon entry in the water. All seals were closed after resurfacing during the NEAR-DRY-O condition. Both types of suits were made of a Nomex shell, an inner Goretex membrane and a thermally insulative liner. In addition to the immersion suits, all subjects wore the following clothing: long polyester underwear (top and bottom), one-piece cotton flying suit, neoprene boots and hood, and inflatable mitts.

Procedures

Before each immersion, the subjects were dressed with sensors and the appropriate clothing and then weighed on an electronic scale. Each immersion consisted of a series of 4 events that were completed within a period of about 1.5 hr. The purpose of the immersion was to simulate the series of evens experienced by an aircrew during a helicopter crash at sea. The first event, simulating the crash, was a helicopter simulator egress into the sea. The egress consists of moving the subject from the ship deck to the sea water while harnessed inside the simulator. Once touching the water, the simulator was inverted under water and the subject counted to 5 before releasing himself from the chair, exiting the simulator and resurfacing.
After resurfacing, the subject inflated his life vest, put his mitts and started swimming to a one-man life raft positioned 20 m away from the main ship. After reaching the life raft, the subject boarded it and then immediately exited it to return to the water. Finally, the subject was immersed for 1-hr, un-tethered and using a natural floating position. The subjects were used in pair during the immersions and were closely monitored by a rescue crew on board of a fast-craft. The main ship was following the subjects to a distance of about 500 m in order to be within a 5 min rescue time.

Following the immersion, the subject boarded the fast-craft and returned to the main ship where they were sprayed with fresh water (to consistently saturate the outside of the suit) and weighed following a 2-min waiting period.

Physical and Physiological Variables Measured

During all immersions, the following physical parameters were continuously monitored from the main ship: air temperature, water temperature about 50 cm under the water surface, and wave height.
Water leakage into the suit was estimated by weighing the fully dressed subject before and after each immersion test on an electronic scale accurate to ± 5g. To minimize the effect of the mass fluctuation caused by the movement of the ship on the water leakage estimation, the mass of the subject was recorded every second for a period of 30 sec while seating still on a chair fixed on the scale platform, and an average mass was calculated. In addition, the average mass of the subject was compared to the average mass of a manikin of a similar and known weight measured simultaneously. The post-immersion weight was corrected for the water saturation of the outer layer of the suits.

During each test, skin temperature and heat flow (HFTs; Concept Engineering, Old Saybrook, CT, USA) from 12 sites according to the Hardy and Dubois formula (3) were continuously monitored, in addition to the outside surface temperatures on the suits at those 12 sites, the rectal temperature (Pharmaseal 400 series, Baxter, Valentia, CA, USA) and the heart rate (Polar heart rate monitor; Polar Electro, Stamford, CT, USA). All the temperature and heat flow data were recorded and saved on small data loggers.

The thermal resistances of the suit were measured according to a method previously described (4). Briefly, the thermal resistances were measured from the skin heat loss data and the temperature difference between the skin and the outside surface of the suits.

Statistical Analyses

A one-way ANOVA for repeated measures was used to compare conditions DRY, NEAR-DRY-C and NEAR-DRY-O. These analyses were done for the dependent variables mean skin temperature, mean heat flow, rectal temperature, heart rate, water leakage and thermal insulation of the suits. Results were considered statistically significant at $p \leq 0.05$ (using the Greenhouse-Geisser adjustment for repeated measures). A Newman Keuls post-hoc test was used to determine where was the significance. All values are presented as mean ± SE.

Results

During the last 10 min of the immersions, the rectal temperature was not different between the three conditions averaging 37.3 ± 0.1°C for DRY, 37.3 ± 0.1°C for NEAR-DRY-C and 36.7 ± 0.3°C for NEAR-DRY-O, although the data from the last condition tends to be lower.

The average skin temperature and skin heat loss from 12 sites on the body were significantly lower for the MAC 200 suit than for the dry suit (26.4 ± 1.1°C, 147 ± 8W/m^2) and lower for the NEAR-DRY-O (21.4 ± 1.2°C, 188 ± 5 W/m^2) than the NEAR-DRY-C condition (23.5 ± 0.9°C, 174 ± 5 W/m^2) (Fig. 1, 2).

The heart rate was significantly higher for the NEAR-DRY-O (96.2 ± 1.6 beats/min) as compared to the two other conditions (91.6 ± 1.6 beats/min for DRY; 90.4 ± 2.3 beats/min for NEAR-DRY-C).

The thermal resistances of the suit were 0.95 ± 0.14, 0.69 ± 0.13 and 0.58 ± 0.09 Clo for DRY, NEAR-DRY-C and NEAR-DRY-O conditions, respectively, with the thermal resistance being significantly lower ($p \leq 0.05$) for the NEAR-DRY conditions (Fig. 3). The decrease in insulation for the NEAR-DRY-O condition was attributed to a significantly larger water leakage through the seals (1.37 ± 0.10 L) as compared to the other conditions (DRY: 0.41 ± 0.11 L; NEAR-DRY-C: 0.35 ± 0.11 L) (Fig. 4).

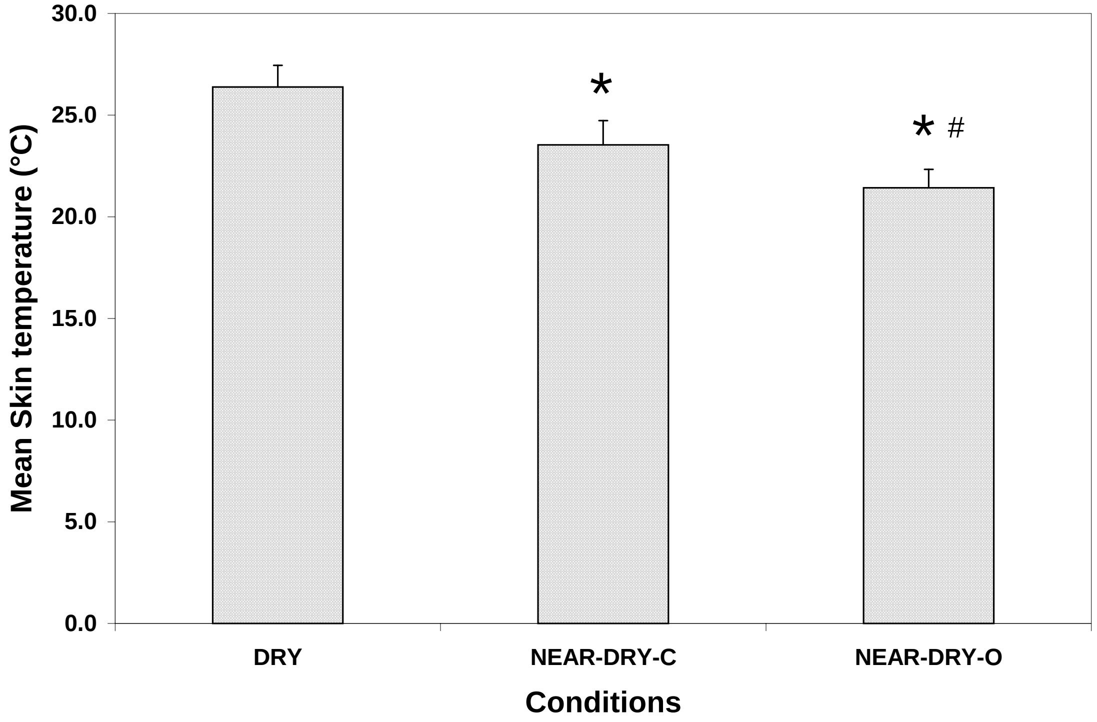

Figure 1. Mean skin temperature (±SE) during the last 10 min period of the 1-hr immersion in 3°C water for all conditions tested at sea. n = 7. *: significantly different from the DRY condition; #: significantly different from the NEAR-DRY-C condition.

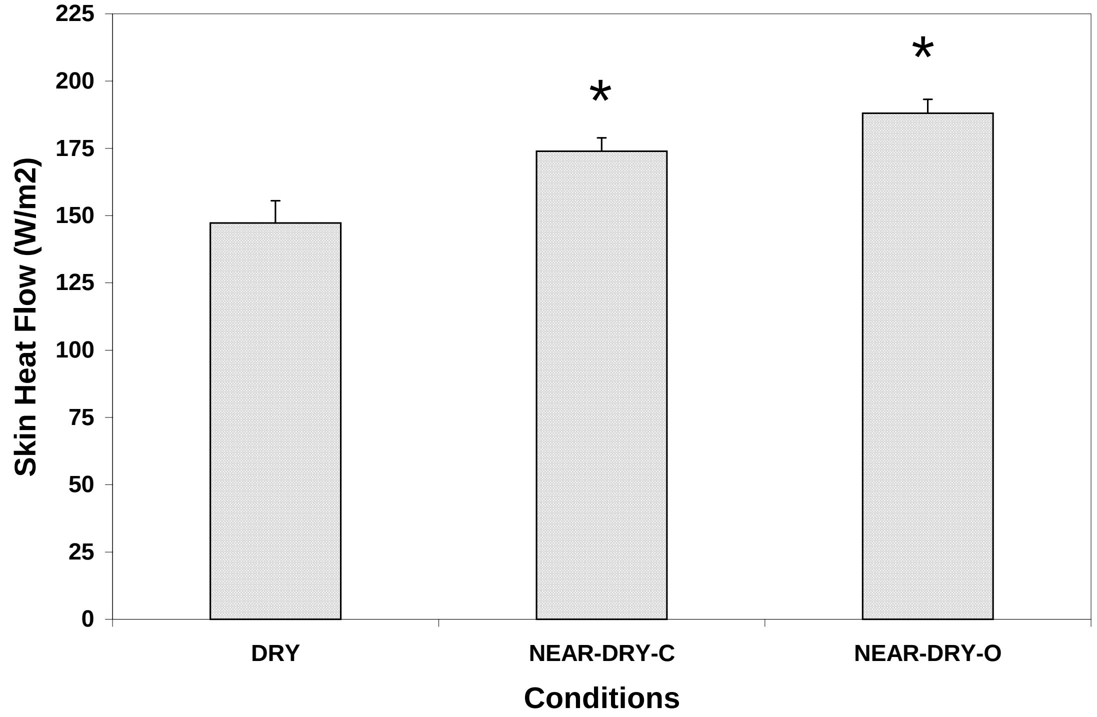

Figure 2. Mean skin heat flow (±SE) during the last 10 min period of the 1-hr immersion in 3°C water for all conditions tested at sea. n = 7. *: significantly different from the DRY condition.

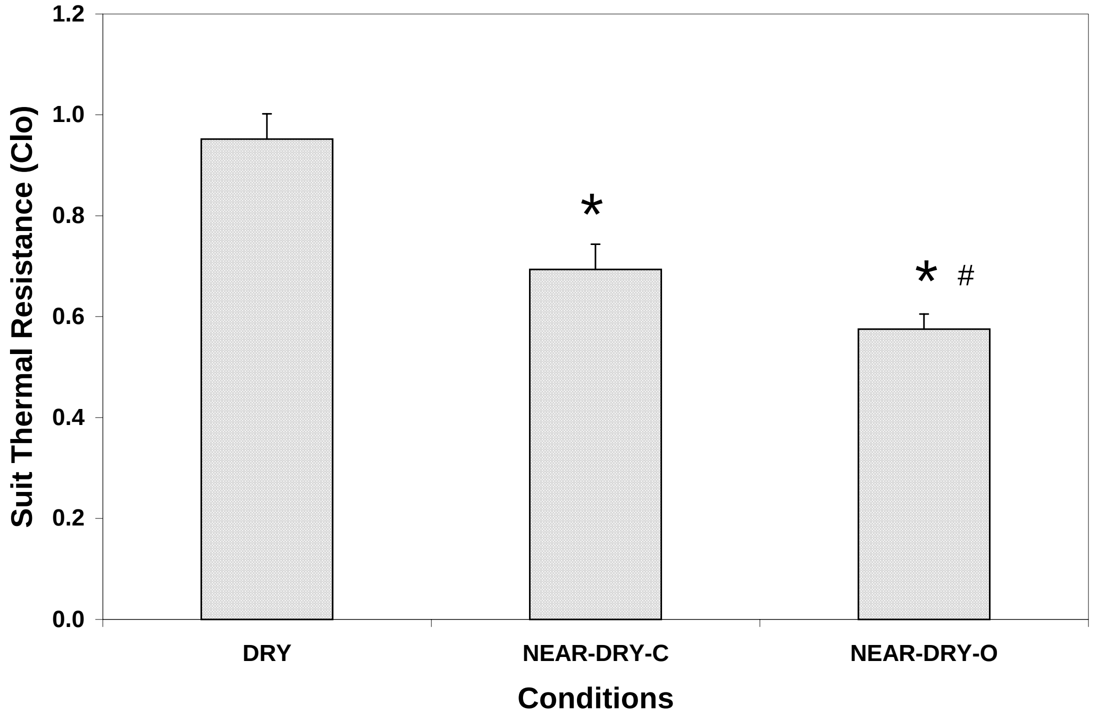

Figure 3. Suit thermal resistance (±SE) during the last 10 min period of the 1-hr immersion in 3°C water for all conditions tested at sea. n = 7. *: significantly different from the DRY condition; #: significantly different from the NEAR-DRY-C condition.

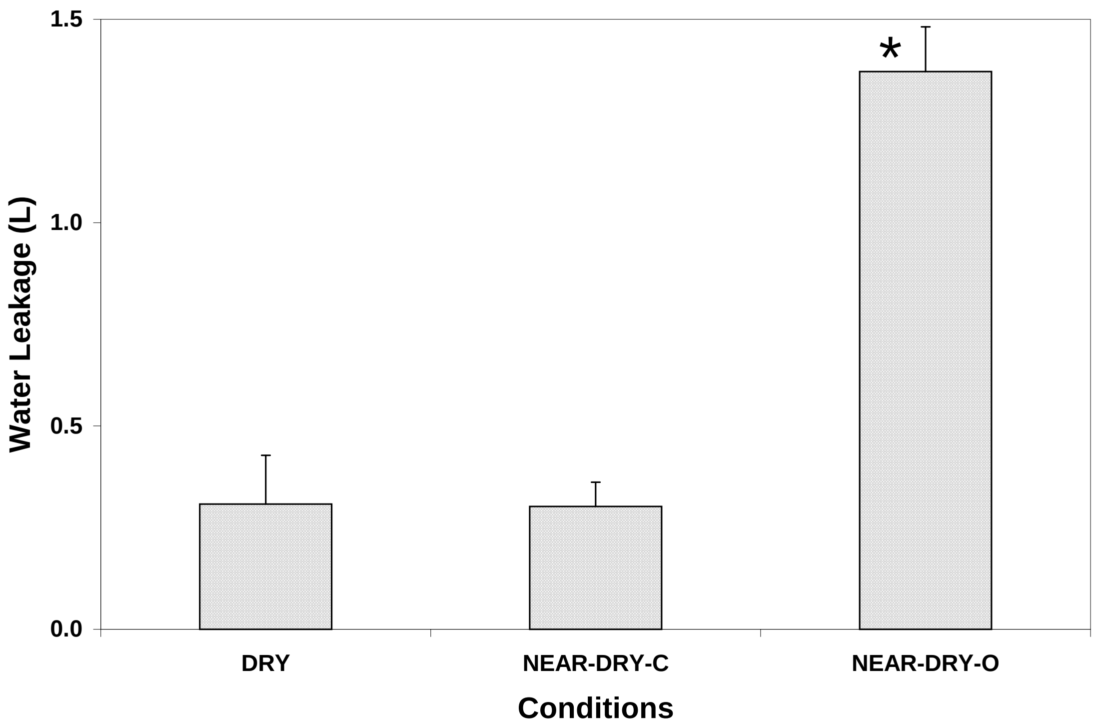

Figure 4. Water leakage into the suits (±SE) estimated from the difference between the pre and post immersion weight of the subjects. n = 7. *: significantly different from the DRY condition.

Discussion and Conclusion

The results from the present study show that when tested at sea during a simulated accidental cold water immersion, the nearly dry suit used in the closed mode did not promote more water egress into the suit as compared to a dry suit. The water leakage observed for the dry suit during this study may seems excessive (0.41 ± 0.11 L), but one has to keep in mind that the suits were tested in a very realistic scenario with a number of self-rescue exercises that promoted water egress. In addition, the dry suits used were not new, but were considered serviceable and had been used by aircrew for a minimum period of three months prior to the study. The same applies to the MAC 200 immersion suits tested. This was intentionally done to further underline the practice dimension of this study. When the neck and wrist seals were open upon entry in the water and closed upon resurfacing, the water leakage was multiplied by a factor of nearly 4. This scenario simulated a situation where the aircrew may have been unconscious or did not have the time to close his seals upon the entry in water.

Despite a similar water leakage, the MAC 200 caused a greater cold stress as compared to the DRY suit condition as reflected by the various physiological parameters (see Fig. 1 and 2). This could be explained by a lower thermal resistance of the MAC 200 immersion suit as compared to the dry suit (see Fig 3). The greater water leakage into the MAC 200 immersion suit during the NEAR-DRY-O condition would explain the further decrease in thermal resistance during that condition.

It was concluded that the nearly dry suit concept, while maintaining a greater comfort when the seals were opened before immersion, successfully limited the water leakage into the suit to a level observed with a dry suit when the seals were closed upon entry in water. The thermal insulation provided by the nearly dry suit is lower than the insulation provided by the dry suit, but not inferior to 0.75 Clo, the recommended insulation to obtain adequate thermal protection in cold water. When the seals of the nearly dry suit were opened before entry in water, the resulting water leakage could significantly decrease the survival time by a factor of two, based on the results from a prediction model (5).

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What is the Survival Suit Designed to Do, and Will it Work for Me in the Event of a Ditching or Ship Abandonment?

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SUMMARY
Three hundred and fifty seven people attended a series of practical survival courses at Survival Systems Ltd., Dartmouth, Nova Scotia between January and June, 2001. Each of the attendees earns their living either working on, or flying over water. During the courses, they wore a variety of survival suits: a helicopter passenger suit; a marine, one-size-fits-all ship abandonment suit; or a military constant wear survival suit. At the beginning and the end of the course, a questionnaire was administered to enquire about (a) the reasons for wearing such a suit, (b) the ergonomics of the suit, and (c) how much confidence they had that the suit would do its job in the case of ship abandonment or helicopter ditching. Pre-course, little was known about the four stages of immersion, but the anecdotal evidence that there was general dissatisfaction with the suits was not generally borne out by the results. Water integrity was better than expected; this can be attributed to better manufacturing procedures, fabrics and standards. An interesting finding was that those people with small wrists or wearing a suit with slack fit of the wrist seal, benefited from tightening the seal with duct tape. The opinions on the ergonomics of the suits followed a normal distribution curve, with the majority of people expressing a relatively good opinion. Most people had confidence that they would survive in them. Post course, the degree of knowledge of the dangers of sudden cold water immersion had improved, but will require re-testing at a later date to investigate the retention factor.

INTRODUCTION
From Biblical times until the middle of the 20th Century, loss of life from cold water immersion was generally ignored. Finally, in 1943, the British Medical Research Committee (Reference 12) published a pamphlet on "The Guide to the Preservation of Life at Sea After Shipwreck". This was based on the observations of naval medical officers who had treated survivors, and on 279 survivor interviews. This document was the basis from which all the modern physiological research has been conducted on cold water immersion.

After the Second World War, two other reports were to follow that revealed the shocking loss of life at sea which could have been prevented. The first was the Talbot Report (1946) (Reference 13). This study showed

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the inadequacy of the RN lifebelt and the Carley type floats. Over 30 000 men died after escaping from their ships, in other words, during the survival phase. The second study was the Medical Research Committee report by McCance et al (1956) which investigated “The Hazards to Men in Ships Lost at Sea 1940 – 1944”. This examined in greater detail the cause of death at sea (Reference 10).

The pioneering post-war work was conducted under the auspices of the Royal Navy Personnel Research Committee and subsequently the Royal Navy Institute of Naval Medicine. This was summarized in Professor Keatinge’s monograph (1969) (Reference 9). As a result of all the aforementioned information, it had become clear that the human body cannot maintain its internal body temperature when immersed in water below 25ºC when conscious and shivering. The body temperature must progressively fall until death occurs. However, there was much more to the problem than a drop in the body core temperature.

Golden and Hervey (1981) (Reference 7) identified four distinct stages in which a human immersed in cold water may become incapacitated and die. The four stages are: 1) Initial Immersion (cold shock); 2) Short-Term Immersion (swimming failure); 3) Long-Term Immersion (hypothermia); and 4) Post-Rescue Collapse. What is important to note is that stages 1, 2 and 4 were largely regarded as of academic interest only; and did not have a large effect on survival policy, international regulations, or survival equipment.

All efforts of the Navies, Merchant Services, and the International Maritime Organizations concentrated on predicting the onset of hypothermia. There is still no consideration given to the physiological impact resulting from the first two stages of immersion in the design of emergency equipment. For instance, flares are still vacuum packed in polythene bags and, as in the Estonia accident were not usable simply because no one had the grip strength or the tactility to open the bags. For instance, the bailer in the Estonia life raft was wrapped in polythene and after attempting to open it with his teeth; the survivor finally gave up after he had lost several teeth!

So, in spite of very good regulations, very good survival suits, good training programs for such agencies as the Coast Guard, the Red Cross, and the National Life Saving Association, there are still over 140,000 open water deaths each year (Reference 5).

It became apparent that the first two stages of the immersion incident; i.e., cold shock and swimming failure were much more important causes of death than originally interpreted. This has been supported by a number of recent papers by Giesbreicht (1995) (Reference 5), Tipton et al (1992, 1994, 1999), (References 14, 15, 16) and Wallingford (2000) (Reference 17).

Therefore, in order to increase the knowledge of the dangers of the first two stages of immersion, Brooks, in 1997, in conjunction with the Canadian Search and Rescue Secretariat produced a new video titled: “The Cold Facts” to explain the physiological effects and preventative measures to be taken. For three years now, international survival training establishments have used this video.[1]

PURPOSE OF THE STUDY

The first part of this study was designed to enquire of all trainees who attended various survival courses at Survival Systems, Dartmouth, Nova Scotia, how much they were now aware of cold shock, swimming failure, and why they needed to wear survival suits to protect themselves. This was done by administering one questionnaire before and one questionnaire after the course. The second part of the study was related to the work done on the development of a Canadian General Standards Board standard for the improvement of helicopter passenger survival suits. This initial standard was established in 1989 (Reference 3). In 1999, it was revised to include new technology and scientific advancement in clothing technology (Reference 4). However, during the recent revision, the question of fit and sizes of the suit was not addressed. There was no scientific data to suggest that there should be more than the traditional manufactured sizes of small, medium,

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[1] The Cold Facts – Surviving Sudden Cold Water Immersion. Canadian Department of National Defense. Catalogue No. 22-1535C. Available from: Intercom Films. Suite 303, 1650 Younge St., Toronto, Ontario, M4T 2A2.

large, and extra large generally established for the male population. So, after each course, included in the second questionnaire, there were questions asking specifically about fit, comfort, wear, and an overall opinion about their confidence that the suit would do its job properly in the event of abandonment into cold water.

METHOD

Survival Systems delivers regular weekly safety survival courses throughout the year. Class sizes range from 6 to 30 trainees depending on the demand of the military organizations, the offshore oil community, and the Coast Guard. From 1 January 2001 to 30 June 2001, it was decided to canvass the opinion of as many trainees as possible who attended the Basic Survival Training (BST) course (5 days); the Basic Survival Training Refresher (BSTR) course (3 days); the military Aircraft Ditching (ADC) course (2 days); or the Offshore Survival Introduction (OSI) course (1 day).

Two questionnaires were administered. The first one was handed out on the morning of the first day of each course. Apart from basic personal information, the objective was to enquire about the knowledge of the dangers of cold water immersion. It asked:

(a) Basic personal data – name, age, sex, height, weight

(b) If this was the first attendance on a safety survival training course. If not, then date and type of previous course.

(c) What critical temperature of water would you decide to don a survival suit before abandoning ship, rig, or helicopter. [Answer: 15°C]

(d) When suddenly immersed in water, how many stages are there in which you may die. [Answer: 4]

(e) If possible, name the stages identified in question (d). [Answer: cold shock, swimming failure, hypothermia, and post rescue collapse]

(f) Water transfers heat away from the body how many times more rapidly than air. [Answer: 25-27xs]

The objective of this questionnaire was to discover if the trainees knew about the four stages of the immersion incident; that immersion in water below 15°C was particularly dangerous; that a survival suit must always be worn when operating in water at or below this temperature; and the fact that water transfers heat away from the body 25-27 times more rapidly than air, hence the requirement for a dry suit versus a wet suit.

During the week, each trainee was shown the new video in the classroom. Then, depending on which course they attended, they wore one of the following:

- An orange-coloured, commercially available helicopter passenger suit (Figure 1)
- A yellow-coloured, commercially available marine abandonment suit (Figure 2)
- A green-coloured Canadian Forces military helicopter constant wear immersion suit (Figure 3)
- Or, for the offshore oil industry, a combination of both commercially available suits

The orange suit was constructed from 5 mm neoprene foam and a quilted liner bonded to the inside. Closure was achieved with a front zip that finished on the lower edge of the face shield. This had neoprene foam for the wrist seals and the neck as sealed by the hood that made a continuous seal around the face. There were rubber Wellington boots glued onto the trouser legs and it is manufactured in five sizes; extra small, small, medium, large, and extra large. Pockets in the sleeves were provided for gloves.

The yellow survival suit was constructed from urethane-coated nylon and had a 3 mm foam rubber detachable lining. A front zip that ended in the neck seal achieved closure. The neck and wrists were sealed

by 3 mm foam and the soft rubber boots were welded onto the trouser legs. Pockets in the sleeves were provided for gloves. It was a one-size-fits-all, the idea being that it could be stowed on the upper deck and be available for use by anyone who required it.

Finally, the green military aircrew survival suit was constructed from Gortex / Nomex. This relied on neoprene rubber seals for the neck and the wrists. The feet were sealed by a fabric sock. A horseshoe zip that started at the front of one shoulder, ran around the back of the shoulders, and ended up at the front of the other shoulder achieved closure of the suit. This suit is manufactured in 9 sizes.

Figure 1: The orange helicopter passenger suit made in three sizes.

Figure 2: The yellow one-size-fits-all marine abandonment suit.

Figure 3: The green military aircrew immersion suit made in nine sizes.

Wearing one or more of the suits, depending on the course, each trainee was required to do (a) the standard marine exercises such as jumping off the 3 metre tower into the pool, climbing a Jacobs ladder, and launching and entering the standard marine life raft in the pool; (b) all the helicopter underwater training exercises such as strapping into the helicopter underwater escape trainer, assuming the crash position, locating the emergency escape exit underwater, jettisoning the window or door, undoing the seat harness, and escaping; and (c) all the survival activities at sea such as abandoning ship from the Fast Rescue Craft (FRC) into the Atlantic Ocean off Halifax Harbor in whatever weather conditions occurred that day, entering into a life raft and then being recovered by the FRC.

In other words, each trainee wore the suits under a variety of different physical conditions and weather conditions. The coldest sea day in January was -20°C and the sea water was +2°C and the warmest sea day in June was +24°C and the sea water was +11°C.

Following the completion of the course, a second questionnaire was administered.

This was divided into two parts. The first part was basically a repeat of the first questionnaire to ascertain how much knowledge the trainees had gained from the video, the classroom and pool instruction. It asked only three questions:

a) At what critical water temperature would you decide to don a survival suit?

b) List in chronological order the sequences in which post rescue collapse, swimming failure, hypothermia, and cold shock occur.

c) Water transfers heat away from the body how many more times rapidly than air?

The second series of questions was related to the ergonomics of the survival suit, interface of the lifejacket, and ease or difficulty of strapping in and escaping from the helicopter underwater escape trainer. It asked about:

a) Fit of the suit
b) Ease of donning and doffing
c) Ease of operating the zip
d) Comfort and fit of the neck seal
e) Comfort and fit of the wrist seal
f) Comfort and fit of the gloves
g) Comfort and fit of the boots
h) Opinion of the general feel and ergonomics of the suit
i) Mobility
j) Interface with the lifejacket
k) Ease of strapping into the helicopter seat
l) Ease of escape from the helicopter underwater escape trainer
m) Ease of climbing into the life raft
n) Dryness of the suit
o) Confidence that the person could survive in the suit

The trainees were asked to rank all these factors on a scale of 1 to 5, where one was very good and 5 was very poor.

The answers from the questions were entered into an Excel spread sheet and statistically analyzed by Minitab (Minitab Inc.).

RESULTS

A total of 357 people completed the questionnaire between 1 January 2001 and 30 June 2001. There were 342 males and 15 females. Their ages ranged from 19 to 63 years old. When split into the four categories of training courses that they attended, there were 173 people who attended the Basic Survival Training (BST) course; 123 people who attended the Basic Survival Training Refresher (BSTR) course; 47 military people who attended the Aircraft Ditching (ADC) course; and there was just one group of 14 people who attended the Offshore Survival Introduction (OSI) course.

EXAMINATION OF THE RESULTS OF THE FIRST (KNOWLEDGE) QUESTIONAIRE

Male Trainees' Data

Course	Attendees	Age Range	Height Range	Weight Range
BST	164	19-63	62"-79"	115-300 lbs
BSTR	119	21-60	63"-79"	140-265 lbs
ADC	46	24-52	65"-75"	150-260 lbs
OSI	13	29-49	65"-74"	150-250 lbs

Female Trainees' Data

Course	Attendees	Age Range	Height Range	Weight Range
BST	9	22-41	60"-69"	120-220 lbs
BSTR	4	21-38	61"-70"	120-205 lbs
ADC	1	39	61"	150 lbs
OSI	1	Not provided	60"	108 lbs

<u>Basic Survival Training Course (BST)</u>

<u>Water Temperature</u>

From the possible temperatures of 25°C, 20°C, 15°C, 10°C, 5°C, 0°C, or Don't Know at what temperature to decide to don a survival suit if one had to abandon ship, rig, or helicopter, 37 people (21.4%) identified the correct water temperature (15°C); 79 people (45.7%) gave an incorrect temperature; and 57 people (33%) admitted they did not know. The most common incorrect temperature chosen was 25°C chosen by 37 people (21.4%) and 20°C chosen by 18 people (10.4%).

<u>Number of Stages of Immersion</u>

From possible answers of 1, 2, 3, 4, 5, 6 or Don't Know how many physiological phases there are during which one may die when suddenly immersed in cold water, 10 people (5.8%) identified correctly that there were 4 phases; 38 people (22.5%) gave an incorrect number; and 125 people (72.3%) admitted they did not know. (Figure 4)

<u>Naming the Stages of Cold Water Immersion</u>

When asked to name the 4 physiological phases, no one (0%) named all 4 phases correctly; 41 people (23.7%) identified at least one of the phases correctly; and 132 people (76.3%) admitted they did not know. The most common correct answer was hypothermia. (Figure 5)

<u>Water Heat Transfer</u>

From possible answers of 3xs, 10xs, 17xs, 25xs, 33xs, or Don't Know how many times more rapidly (than air) water transfers heat away from the body, 14 people (8.1%) identified 25-27 times as the correct answer; 59 people (34.1%) gave an incorrect answer; and 100 people (57.8%) admitted they did not know.

Basic Survival Training Refresher Course (BSTR)

Water Temperature
From the possible temperatures of 25°C, 20°C, 15°C, 10°C, 5°C, 0°C, or Don't Know at what temperature to decide to don a survival suit if one had to abandon ship, rig, or helicopter, 18 people (14.6%) identified the correct water temperature (15°C); 82 people (66.6%) gave an incorrect temperature; and 23 people (18.7%) admitted they did not know. The most common incorrect temperature chosen was 25°C chosen by 34 people (27.6%) and 20°C chosen by 31 people (25.2%).

Number of Stages of Immersion
From possible answers of 1, 2, 3, 4, 5, 6 or Don't Know how many physiological phases there are during which one may die when suddenly immersed in cold water, 21 people (17.0%) identified correctly that there were 4 phases; 38 people (31.0%) gave an incorrect number; and 64 people (52.0%) admitted they did not know. (Figure 4)

Naming the Stages of Cold Water Immersion
When asked to name the 4 physiological phases, one (0.8%) named all 4 phases correctly; 35 people (28.5%) identified at least one of the phases correctly; and 87people (70.7%) admitted they did not know. The most common correct answer was hypothermia. (Figure 5)

Water Heat Transfer
From possible answers of 3xs, 10xs, 17xs, 25xs, 33xs, or Don't Know how many times more rapidly (than air) water transfers heat away from the body, 11 people (8.9%) identified 25-27 times as the correct answer; 49 people (39.9%) gave an incorrect answer; and 63 people (51.2%) admitted they did not know.

Aircraft Ditching Course (ADC)

Water Temperature
From the possible temperatures of 25°C, 20°C, 15°C, 10°C, 5°C, 0°C, or Don't Know at what temperature to decide to don a survival suit if one had to abandon ship, rig, or helicopter, 16 people (34.0%) identified the correct water temperature (15°C); 23 people (48.9%) gave an incorrect temperature; and 8 people (17.0%) admitted they did not know. The most common incorrect temperature chosen was 25°C chosen by 8 people (17.0%) and 20°C chosen by 11 people (23.4%).

Number of Stages of Immersion
From possible answers of 1, 2, 3, 4, 5, 6 or Don't Know how many physiological phases there are during which one may die when suddenly immersed in cold water, 4 people (8.5%) identified correctly that there were 4 phases; 10 people (21.3%) gave an incorrect number; and 33 people (70.2%) admitted they did not know. (Figure 4)

Naming the Stages of Cold Water Immersion
When asked to name the 4 physiological phases, no one (0.0%) named all 4 phases correctly; 8 people (17.0%) identified at least one of the phases correctly; and 39 people (83.0%) admitted they did not know. The most common correct answer was hypothermia. (Figure 5)

Water Heat Transfer
From possible answers of 3xs, 10xs, 17xs, 25xs, 33xs, or Don't Know how many times more rapidly (than air) water transfers heat away from the body, 13 people (27.7%) identified 25-27 times as the correct answer; 16 people (34.1%) gave an incorrect answer; and 18 people (38.3%) admitted they did not know.

Offshore Survival Introduction (OSI)

Water Temperature

From the possible temperatures of 25°C, 20°C, 15°C, 10°C, 5°C, 0°C, or Don't Know at what temperature to decide to don a survival suit if one had to abandon ship, rig, or helicopter, 1 person (7.0%) identified the correct water temperature (15°C); 4 people (28.5%) gave an incorrect temperature; and 9 people (64%) admitted they did not know. The most common incorrect temperature chosen was 25°C chosen by 1 person

Number of Stages of Immersion

From possible answers of 1, 2, 3, 4, 5, 6 or Don't Know how many physiological phases there are during which one may die when suddenly immersed in cold water, 3 people (21.4%) identified correctly that there were 4 phases; 1 person (7.1%) gave an incorrect number; and 10 people (71.4%) admitted they did not know. (Figure 4)

Naming the Stages of Cold Water Immersion

When asked to name the 4 physiological phases, no one (0%) named all 4 phases correctly; 5 people (35.7%) identified at least one of the phases correctly; and 9 people (64.3%) admitted they did not know. The most common correct answer was hypothermia. (Figure 5)

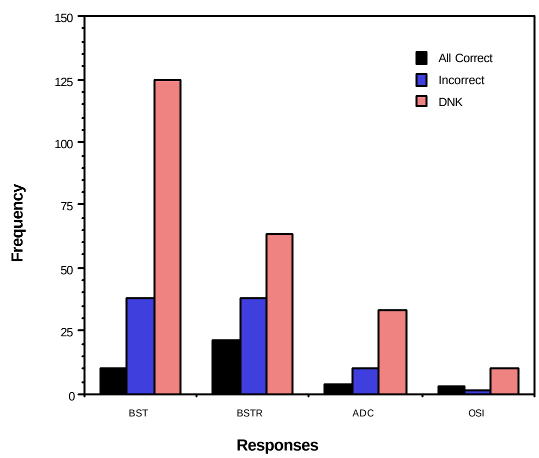

Figure 4: Number of physiological stages of immersion.

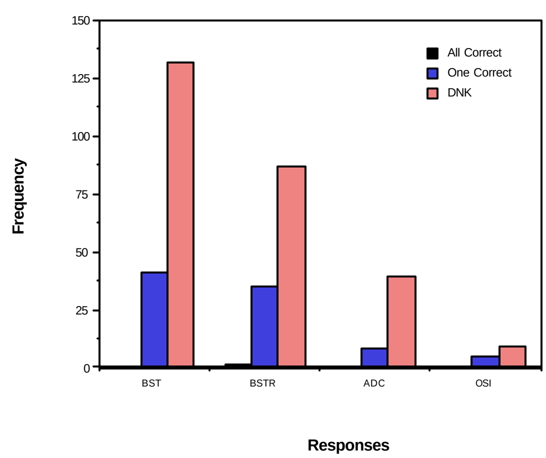

Figure 5: Naming the physiological stages of immersion.

EXAMINATION OF THE RESULTS OF THE SECOND (KNOWLEDGE & ERGONOMICS) QUESTIONAIRE

On completion of the course, the following responses were elucidated from the trainees answering the second questionnaire. These are listed in Tables 1-15 below.

Table One: Fit of the Suit

Course	Suit	Scale				
		1 (Best)	2	3	4	5 (Worst)
BST	Orange	17(11%)	53(34.4%)	49(31.8%)	20(13%)	15(9.7%)
	Yellow	44(25%)	69(40.4%)	38(22.2%)	14(8.2%)	6(3.5%)
BSTR	Orange	14(14.3%)	42(42.7%)	27(27.6%)	13(13.3%)	2(2.0%)
	Yellow	25(20.3%)	46(37.4%)	37(30.1%)	12(9.8%)	3(2.4%)
ADC	Green	6 (12.8%)	26(55.3%)	11(23.4%)	2(4.3%)	2(4.3%)
OSI	Yellow	5 (38.5%)	4(30.8%)	1(7.7%)	2(15.4%)	1(7.7%)

Table Two: Donning of the Suit

Course	Suit	Scale				
		1 (Very Easy)	2	3	4	5 (Very Difficult)
BST	Orange	25(16.2%)	79(51.3%)	33(21.4%)	14(9.1%)	3(2.0%)
	Yellow	42(24.7%)	83(48.8%)	32(18.8%)	9(5.3%)	4(2.4%)
BSTR	Orange	22(22.5%)	51(52.0%)	22(22.5%)	3(31.1%)	0(0.0%)
	Yellow	31(25.8%)	60(50.0%)	22(18.3%)	7(5.8%)	0(0.0%)
ADC	Green	2(4.3%)	17(36.2%)	15(31.9%)	9(19.2%)	4(8.3%)
OSI	Yellow	5(38.5%)	3(23.1%)	5(38.5%)	0(0.0%)	0(0.0%)

Table Three: Operating the Zip

Course	Suit	Scale				
		1 (Very Easy)	2	3	4	5 (Very Difficult)
BST	Orange	20(12.9%)	68(43.9%)	44(28.4%)	19(12.3%)	4(2.6%)
	Yellow	42(24.6%)	74(43.3%)	31(18.1%)	20(11.7%)	4(2.3%)
BSTR	Orange	33(33.7%)	39(39.8%)	21(21.4%)	5(5.1%)	0(0.0%)
	Yellow	38(31.4%)	60(49.6%)	15(12.4%)	8(6.6%)	0(0.0%)
ADC	Green	0(0.0%)	3(6.4%)	6(12.8%)	20(42.6%)	18(38.3%)
OSI	Yellow	3(21.4%)	6(42.9%)	2(14.3%)	1(7.1%)	5(14.3%)

Table Four: Comfort of the Neck Seal

Course	Suit	Scale				
		1 (Very Comfortable)	2	3	4	5 (Very Uncomfortable)
BST	Orange	12(7.8%)	33(21.6%)	58(37.9%)	34(22.2%)	16(10.5%)
	Yellow	19(11.1%)	45(26.3%)	37(21.6%)	51(29.8%)	19(11.1%)
BSTR	Orange	13(13.3%)	32(32.7%)	36(36.7%)	12(12.2%)	5(5.1%)
	Yellow	21(17.4%)	35(28.9%)	33(27.3%)	22(18.2%)	10(8.3%)
ADC	Green	4(8.5%)	10(21.3%)	17(36.2%)	12(25.5%)	4(8.5%)
OSI	Yellow	2(14.3%)	3(21.4%)	4(28.6%)	4(28.6%)	1(7.1%)

Table Five: Comfort of the Wrist Seal

Course	Suit	Scale				
		1 (Very Comfortable)	2	3	4	5 (Very Uncomfortable)
BST	Orange	33(21.9%)	64(42.4%)	32(21.2%)	16(10.6%)	6(4.0%)
	Yellow	63(36.8%)	63(36.8%)	28(16.4%)	12(7.0%)	5(2.9%)
BSTR	Orange	28(29.5%)	33(34.7%)	22(23.2%)	7(7.4%)	5(5.3%)
	Yellow	43(35.8%)	43(35.8%)	23(19.2%)	8(6.7%)	3(2.5%)
ADC	Green	6(12.8%)	24(51.1%)	10(21.3%)	5(10.6%)	2(4.3%)
OSI	Yellow	3(21.4%)	7(50.0%)	0(0.0%)	1(7.1%)	3(21.4%)

Table Six: Comfort and Fit of the Gloves

Course	Suit	Scale				
		1 (Very Comfortable)	2	3	4	5 (Very Uncomfortable)
BST	Yellow	9(5.3%)	33(19.4%)	44(25.4%)	47(27.7%)	5(21.8%)
BSTR	Yellow	10(8.7%)	19(16.5%)	26(22.6%)	33(28.7%)	27(23.5%)
OSI	Yellow	3(33.3%)	3(33.3%)	1(11.1%)	2(22.2%)	0(0.0%)

Table Seven: Fit of the Boots

Course	Suit	Scale				
		1 (Very Comfortable)	2	3	4	5 (Very Uncomfortable)
BST	Orange	30(19.9%)	56(37.1%)	28(18.5%)	15(9.9%)	22(14.5%)
	Yellow	22(12.9%)	59(34.5%)	49(28.7%)	23(13.5%)	18(10.5%)
BSTR	Orange	21(22.8%)	31(33.7%)	21(22.8%)	11(12.0%)	8(8.7%)
	Yellow	16(13.1%)	30(24.6%)	24(23.8%)	29(23.8%)	18(14.8%)
OSI	Yellow	5(35.7%)	1(7.1%)	6(42.9%)	1(7.1%)	1(7.1%)

Table Eight: Overall Opinion of the Survival Suit

Course	Suit	Scale				
		1 (Very Comfortable)	2	3	4	5 (Very Uncomfortable)
BST	Orange	19(13.6%)	55(39.3%)	41(29.3%)	16(11.4%)	9(6.4%)
	Yellow	46(26.9%)	82(48.0%)	30(17.5%)	10(5.0%)	3(1.8%)
BSTR	Orange	12(12.2%)	49(50.0%)	27(27.6%)	10(10.2%)	0(0.0%)
	Yellow	27(22.3%)	58(47.9%)	26(21.5%)	8(6.6%)	2(1.7%)
ADC	Green	2(4.3%)	17(36.2%)	20(42.6%)	8(17.0%)	0(0.0%)
OSI	Yellow	7(50.0%)	3(21.4%)	2(14.3%)	2(14.3%)	0(0.0%)

Table Nine: Mobility in the Survival Suit

Course	Suit	Scale				
		1 (Very Easy)	2	3	4	5 (Very Difficult)
BST	Orange	23(14.9%)	69(44.8%)	39(25.3%)	15(9.7%)	8(5.2%)
	Yellow	46(27.0%)	85(49.7%)	27(15.8%)	12(7.0%)	1(0.6%)
	Green	5(10.6%)	32(68.1%)	7(14.9%)	3(6.4%)	0(0.0%)
BSTR	Orange	17(17.4%)	49(50.0%)	23(23.5%)	6(6.1%)	3(3.1%)
	Yellow	33(26.8%)	63(51.2%)	21(17.1%)	6(4.9%)	0(0.0%)
ADC	Green	2(4.3%)	17(36.2%)	20(42.6%)	8(17.0%)	0(0.0%)
OSI	Yellow	6(42.9%)	4(28.6%)	2(14.3%)	2(14.3%)	0(0.0%)

Table Ten: Ease of Strapping into the Helicopter Underwater Escape Trainer

Course	Suit	Scale				
		1 (Very Easy)	2	3	4	5 (Very Difficult)
BST	**Orange**	33(19.9%)	66(39.8%)	48(28.9%)	17(10.2%)	2(1.2%)
BSTR	**Orange**	19(17.8%)	42(39.3%)	31(29.0%)	13(12.2%)	2(1.9%)
ADC	**Green**	4(16.7%)	12(50.0%)	8(33.3%)	0(0.0%)	0(0.0%)

Table Eleven: Interface with the Lifejacket

Course	Suit	Scale				
		1 (Very Easy)	2	3	4	5 (Very Difficult)
BST	**Orange**	19(11.5%)	78(47.0%)	40(24.1%)	44(14.5%)	5(3.0%)
BSTR	**Orange**	26(24.8%)	44(41.9%)	27(25.7%)	5(4.8%)	3(2.9%)
ADC	**Green**	6(25.0%)	10(41.7%)	6(25.0%)	2(8.2%)	0(0.0%)

Table Twelve: Ease of Escape from the Helicopter Underwater Escape Trainer

Course	Suit	Scale				
		1 (Very Easy)	2	3	4	5 (Very Difficult)
BST	**Orange**	53(32.1%)	79(47.9%)	24(14.6%)	9(5.5%)	0(0.0%)
BSTR	**Orange**	33(30.6%)	53(49.1%)	16(14.8%)	6(5.6%)	0(0.0%)
ADC	**Green**	3(12.5%)	16(66.7%)	5(20.8%)	0(0.0%)	0(0.0%)

Table Thirteen: Ease of Life Raft Entry

Course	Suit	Scale				
		1 (Very Easy)	2	3	4	5 (Very Difficult)
BST	**Yellow**	57(34.3%)	85(51.2%)	19(11.5%)	5(3.0%)	0(0.0%)
BSTR	**Yellow**	39(35.1%)	52(45.1%)	15(13.5%)	3(2.7%)	2(1.8%)

Table Fourteen: Dryness of the Survival Suit

Course	Suit	Scale				
		1 (Very Dry)	2	3	4	5 (Very Wet)
BST	**Orange**	6(8.8%)	19(27.4%)	19(27.9%)	10(14.7%)	14(20.6%)
	Yellow	84(49.4%)	70(41.2%)	9(5.3%)	5(2.9%)	2(1.2%)
BSTR	**Orange**	6(13.6%)	7(15.9%)	11(25.0%)	8(18.2%)	12(27.3%)
	Yellow	71(59.2%)	35(29.2%)	10(8.3%)	1(0.8%)	3(2.5%)
ADC	**Green**	1(2.3%)	7(15.9%)	4(9.1%)	11(25.0%)	21(47.7%)
OSI	**Yellow**	6(42.9%)	5(35.7%)	1(7.1%)	1(7.1%)	1(7.1%)

Table Fifteen: Confidence in the Survival Suits

Course	Suit	Scale				
		1 (Very Confident)	2	3	4	5 (No Confidence)
BST	**Orange**	27(25.0%)	39(36.1%)	27(25.0%)	13(12.0%)	2(1.9%)
	Yellow	76(44.4%)	65(38.0%)	17(9.9%)	8(4.7%)	5(2.9%)
BSTR	**Orange**	24(33.8%)	21(29.6%)	10(14.1%)	14(19.7%)	2(2.8%)
	Yellow	42(35.3%)	36(30.3%)	23(19.3%)	9(7.6%)	9(7.6%)
ADC	**Green**	3(6.5%)	13(28.3%)	23(50.0%)	7(15.2%)	0(0.0%)
OSI	**Yellow**	6(46.2%)	1(7.7%)	2(15.4%)	2(15.4%)	2(15.4%)

Specific answers to the identification of the correct water temperature, identification of the correct water heat transfer question pre and post-course, and the correct listing of the four stages of immersion are illustrated in Figures 6 to 10. Specific illustrations of opinions on ergonomic factors such as fit, interface with the lifejacket, ease of escape from the helicopter underwater escape trainer, overall opinion of the suit, confidence in the suit, and the water integrity are depicted in Figures 11 to 16.

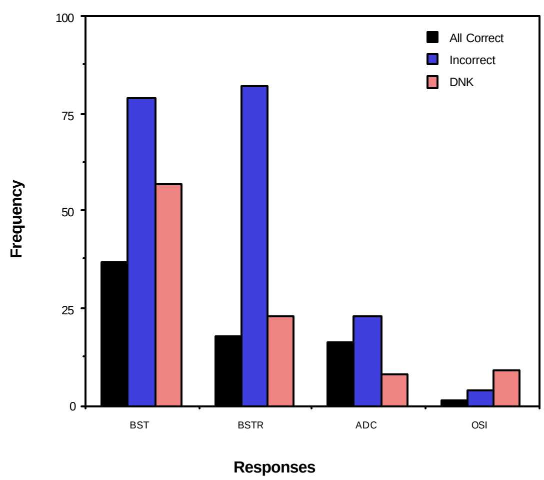

Figure 6: Identifying the correct water temperature (15ºC) for survival suit donning, pre course.

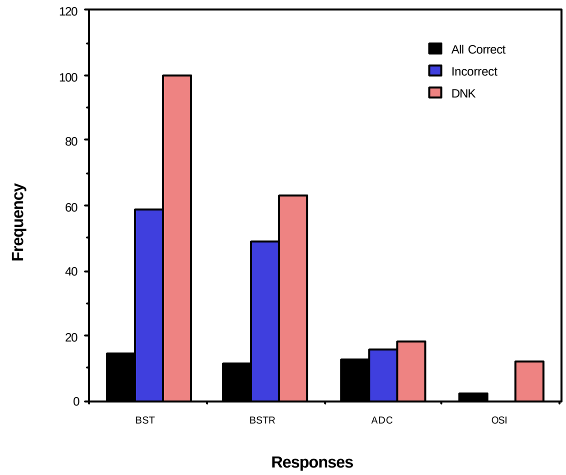

Figure 7: Identifying the water heat transfer factor, pre course.

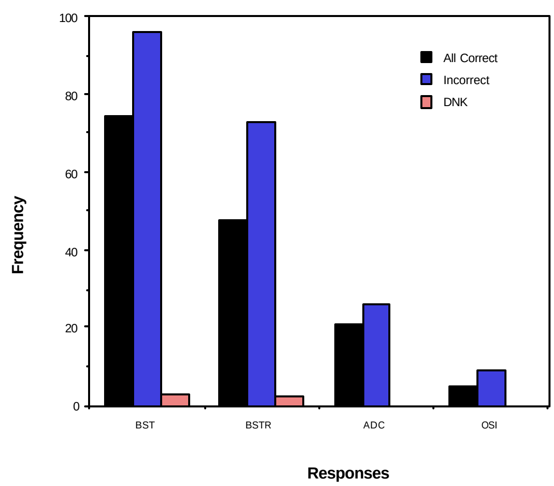

Figure 8: Identifying the correct water temperature (15°C) for survival suit donning, post course.

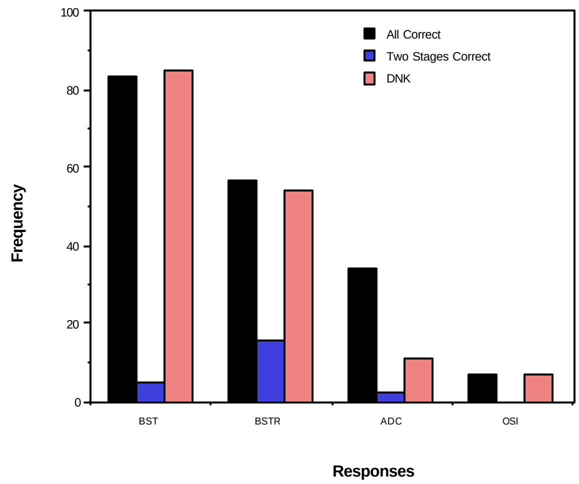

Figure 9: Listing the physiological stages of immersion in chronological order, post course.

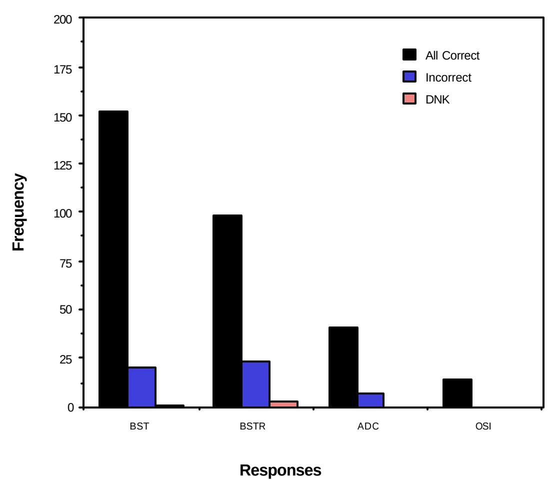

Figure 10: Identifying the correct water heat transfer factor, post course.

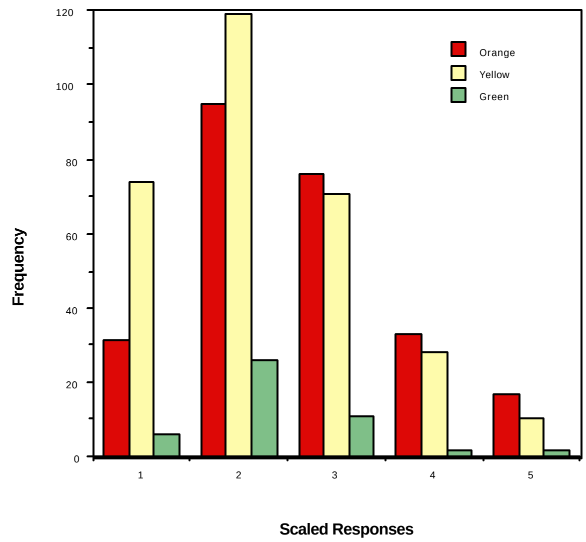

Figure 11: Assessment of the suit fit. (1=very good, 5=very poor)

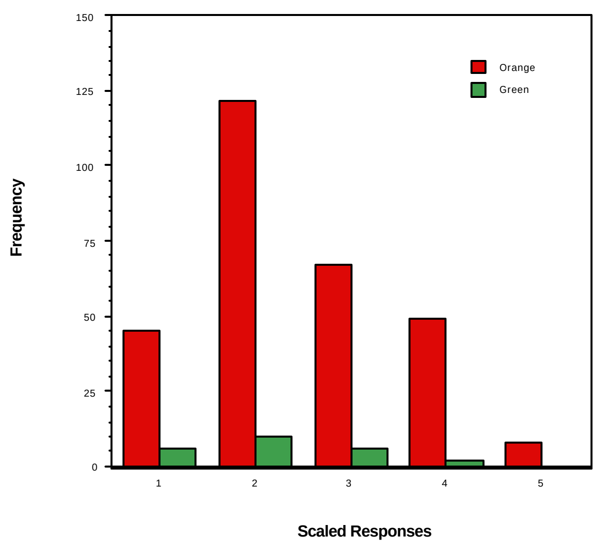

Figure 12: Assessment of the interface with the life jacket. (1=very easy, 5=very difficult)

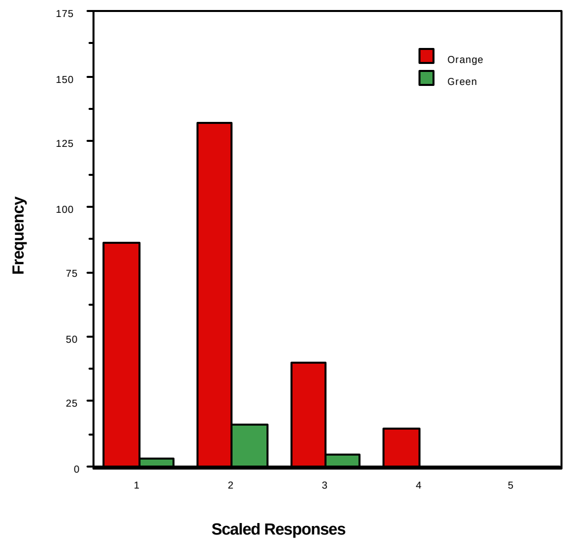

Figure 13: Assessment of the ease of escape from the helicopter underwater escape trainer. (1=very easy, 5=very difficult)

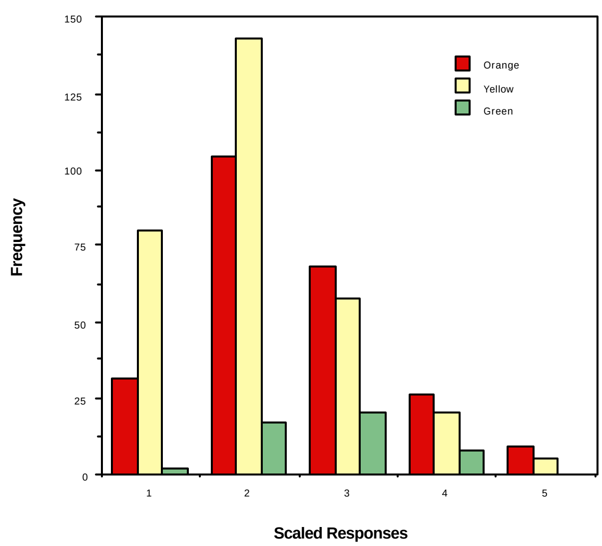

Figure 14: Overall ergonomic opinion of the survival suit. (1=very good, 5=very poor)

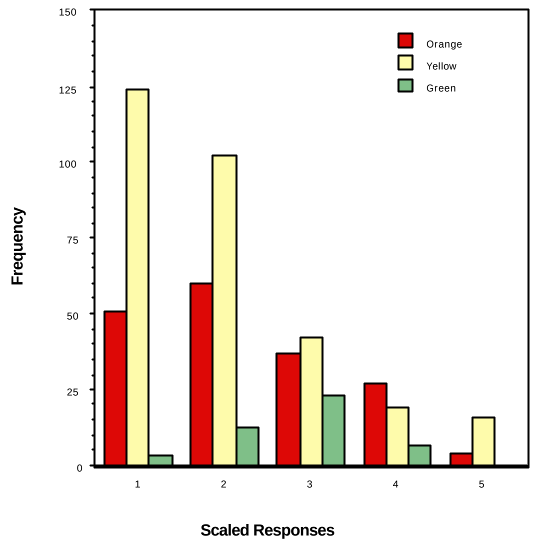

Figure 15: Confidence in the survival suit. (1=absolutely confident, 5=zero confidence)

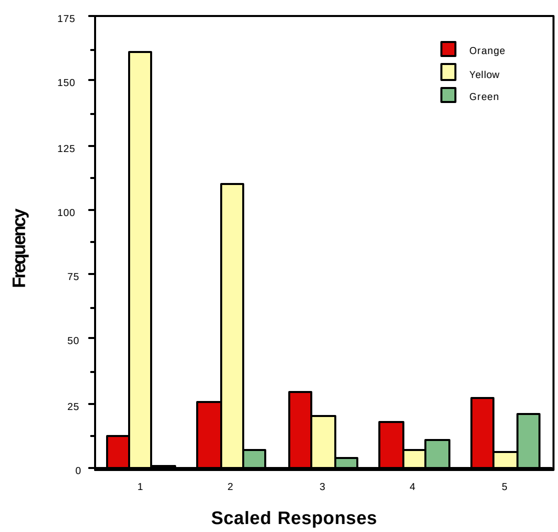

Figure 16: Assessment of the dryness of the suit. (1=completely dry, 5=completely soaked)

DISCUSSION

To the best of our knowledge, this is the first, although preliminary study, to survey a large group of people who all earn their living either in the military, in the offshore oil industry flying over water, or operating small vessels such as Fast Rescue Crafts on the water. Three hundred and fifty-seven people were asked about their basic knowledge of the reasons for wearing a dry type survival suit, their opinions concerning its fit and comfort, the interface with the lifejacket, the ergonomics of strapping into and escape from the helicopter underwater escape trainer, ability to conduct general sea survival duties, and how much confidence they had in the suits. Depending on which of the investigators was available, the questionnaire was administered to as many courses as possible over a six-month period and a very good cross section of ages and physical sizes has been achieved.

Because of the very tight timing schedules in each of the classes to complete the course content, we had to be as fast as possible. The first questionnaire was given on the first day of the course after the basic administration was completed; and the second questionnaire was given after the trainees had showered and changed from their day at sea. This was the principle reason that the questionnaires were short. The second reason was that having worked with this group of people for many years we knew that a longer more detailed questionnaire would result in poorer compliance in answering the questions with enthusiasm and conscientiousness. Their ages ranged from 19 to 63 years old. The range of educational backgrounds was very wide from people who left school at 16 with no educational qualifications to PhD engineers. Unfortunately, with the need to keep the questionnaire as short as possible, it was not possible to enquire in any detail about these factors and then examine whether there was any correlation with the results. As predicted, if the question required a lot of thought, then the response was inadequate. For instance, the enquiry as to whether the person had attended a previous survival course, what type of course and when and where it took place could not be analyzed because of the vague information in the responses. One immediate finding is that only 5% of the people who attended our courses were female. This at least provides some guidelines to suit manufacturers and training course directors of the current male / female ratio for training in Atlantic Canada.

The Knowledge of the Dangers of Sudden Cold Water Immersion and the Fundamental Criteria for Donning a Survival Suit

It did not surprise us that initially only 38 people (10.6%) knew that there were four distinct physiological phases to cold water immersion (Figure 4), and that only one person (0.28%) named all four stages of the immersion incident correctly (Figure 5). This person had been an undergraduate student on the principal author's survival course at Dalhousie the previous year and was attending the course in preparation for working offshore. Two people (0.6%) named three stages correctly; 36 people (10.1%) named two phases correctly; 51 (14.3%) named one stage correctly; and 267 people (74.8%) did not know. It also did not surprise us that hypothermia was the most common correct identification of immersion stages (75 people, 20%). Nor did it surprise us that only 72 people (20.2%) knew that 15ºC was the critical temperature below which all the physiological symptoms become rapidly worse (Figure 6). It also did not surprise us that only 40 people (11.2%) identified that water transferred heat away from the body 25-27 times more rapidly than air (Figure 7).

The encouraging part of this study is that on completion of the course, 148 people (41.5%) knew that the critical water temperature was 15°C (Figure 8). Prior to the course, approximately 60% assigned a temperature of 15°C or above; and following the course, this figure was increased to 92%. One hundred and eighty one people (51.0%) wrote down the correct chronological order in which the four stages occurred (Figure 9), and 17 people (5%) at least identified cold shock and swimming failure as the first two stages. Three hundred and four people (85.2%) correctly identified that 25-27 times was the correct transfer factor (Figure 10). The instructors and the video had a positive effect on increasing the pool of knowledge in this group of people. The results are encouraging especially considering the wide range of educational backgrounds. With a continuous emphasis on the dangers of sudden cold water immersion, it is hoped that the pool of general knowledge will slowly continue to rise. Recently, it has been recommended (Reference 2), that Transport Canada amend the Marine Emergency Duties curriculum to include the Canadian video on cold shock and swimming failure. However, unless people are retested on return for refresher training, it will not be possible to determine the retention factor for this information.

The Overall Fit, Comfort, Dryness, and General Ergonomics of the Survival Suits

Prior to the Ocean Ranger oil rig accident in 1984, the general design of survival suits in Canada was poor; they leaked badly, there were no regulations requiring mandatory use or standards for manufacture. One of the actions arising from the Board of Inquiry was to recommend the introduction of new regulations for helicopter passenger suit systems (Reference 11). The standard was completed in 1989 and revised in 1999. Supporting the Ocean Ranger findings from 15 years ago, there was considerable anecdotal evidence that the survival suits were poorly constructed and leaked badly and that there was a lot of customer dissatisfaction with fit, comfort, and general sartorial elegance. There have always been general complaints about the

comfort of the military immersion suit. This study was fortunate in being able to assess opinions about three fundamentally different types of suits: a military aircrew constant immersion wear suit (green), a commercial constant wear helicopter passenger suit (orange), and a one-size-fits-all marine abandonment suit (yellow). Each was designed for the same purpose, that is, to protect humans in the water from the four physiological phases of cold water immersion, which could cause death. All the suits provided 0.75 immersed CLO of insulation and were manufactured to the latest standard Canadian General Standards Board (Reference 4).

When all the ergonomic factors were examined, the results show a classic normal distribution curve with the trend of responses being between 1 and 3 (very good, good, average) with the remainder being in the 4-5 (poor, very poor) range (Figures 11 through 16). This comes as a surprise and does not bear out the anecdotal evidence. What is more interesting is that the opinions expressed as to the ergonomic appeal of the suits (Figure 14) and the confidence in the suits was much better than expected. The commercial orange and yellow suits were favourably assessed and the green military immersion suit had a fair assessment (Figure 14). It would be expected that the sized orange helicopter passenger suit would have been rated higher than the one-size-fits-all marine abandonment suit. It is postulated this was not the case because of the timing of the second questionnaire. It was administered immediately after the trainees had been in cold sea water in the yellow marine abandonment suit and had all fared well. Therefore, they were basically psychologically pre-disposed to rating the ergonomic facts such as fit, comfort, etc. higher than for the orange suit, which had only been worn in the warm pool, water the previous day (Figure 15). When the responses for the various ergonomic factors 4-5 were compared to the responses for height, weight, age, and sex, there was no correlation. We were particularly interested in peoples opinion as to (a) the interface of the lifejacket with the survival suit because there is no cross reference between lifejacket and survival suit standards, and (b) the ease or difficulty of escape from the helicopter underwater escape trainer with 146 Newtons of positive suit buoyancy. However, the opinions also followed a bell shaped curve with few extreme scores (Figures 12 &13).

Watertight integrity of the suits is a critical factor. It only takes a leakage of one litre of water into the suit to reduce the CLO insulation value by 50% (Reference 1 and 6). Our findings were that, overall, the orange suit was assigned a good or very good factor by 38 people (33.6%); the yellow suit was assigned a good or very good factor by 271 people (88.2%); and the green military suit was assigned a good or very good factor by 8 people (18.2%)(Figure 16).

Although we have no scientific data to compare the leakage results to any other previous large group of people, it is our impression that our new Canadian standard has improved the quality of the suit. Certainly, the crotch area, the zip area and the feet are notoriously difficult to keep watertight for the majority of people. In this study, they remained relatively dry. It is suggested that this is due to the fact that the new standard requires manikin testing with the manikin positioned at 45° in the water. This means there can be no cheating during the regulatory approval process by the manufacturers because zip closure, crotch, feet, neck and wrist seals, are partially, wholly, or most of the time, under water. These are the common areas where leakages occur if the suit is poorly or cheaply constructed.

Considering that the suits worn by each trainee were from our stock of suits; (i.e., not their personal suits), and receive considerable wear each week, it would appear that the manufacturers have taken the quality control message to heart and are making a good quality product. The relatively poorer assessment of the dryness of the orange suit compared to the yellow suit is due to the nearly impossible problem of keeping the suits waterproof from the effects of chlorinated water. The poor assessment of the military immersion suit is because these suits are manufactured from Nomex / Gortex, making them notoriously difficult to keep watertight especially when they are regularly and frequently used in the chlorinated pool water. Furthermore, each military trainee had to do at least twice the number of immersions (eight versus four) in the helicopter underwater escape trainer than the trainees in the civilian BST and BSTR courses. Hence, the greater chance of inducing leakage. Nevertheless, this does demonstrate that the military should be investigating the possibility of using other material than Nomex / Gortex for their suits.

It was a puzzle to us why the one-size-fits-all yellow ship abandonment suit should produce such a favourable response (88%), which is considerably higher than the other two suits on the leakage question. On further examination of the enigma, it was discovered that the instructors routinely take a roll of duct tape to sea with them. Anyone who is wearing a suit with a loose fitting wrist seal or a person with thin wrists is offered the option of tightening the seals with duct tape. This obviously works very well. In the event that there is some time available before abandonment into water, the availability of a roll of duct tape to tighten up any seals or excessive folds in a suit is a good idea. We would recommend that tape be available at ship abandonment stations to do just that.

CONCLUSIONS

1. Questionnaires were given to 357 trainees (342 males and 15 females) who attended one of four marine survival or helicopter ditching courses at Survival Systems Ltd. between January 2001 and June 2001.
2. The questionnaires asked about the knowledge of the dangers of immersion in cold water and the ergonomics of the survival suits that were worn during the course. The suits were fundamentally different: a commercially available sized helicopter passenger suit, a one-size-fits-all marine abandonment suit, and a sized military aircrew constant wear immersion suit.
3. Prior to the course, the answers in the questionnaire confirmed our suspicion that the general knowledge of the dangers of cold water immersion is poorly understood and hypothermia was the only stage of immersion identified.
4. On completion of the course, there was a general improvement in this knowledge with over 50% of students being able to list the chronological order of the four stages correctly.
5. Classroom instruction and videos have improved the knowledge of the dangers of sudden cold water immersion, but trainees will need retesting to assess the retention factor.
6. The general parameters related to the ergonomics of the suits followed a normal distribution curve. Generally, people were relatively satisfied. There was no correlation between extremes of sizes, ages and sex and satisfaction or dissatisfaction.
7. The water integrity of the suits was better than expected. This can be attributed to better standards, manikin testing, better quality control by manufacturers and duct tape used by the instructors.
8. The option of duct tape at ship abandonment stations is a good idea.
9. The overall confidence factor in the suit was higher than anecdotal evidence would suggest.

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Operational and Thermophysiological Needs for Metabolic Heat Dissipation: Ways, Deviations, and Progress

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I. Introduction:

The human body regulates the core temperature neurophysiological by vasomotoric actions, muscle work, general behavior, sweat production and heat production by the brown fat tissue.

The centre is the hypothalamus. Cooling the spine or the head has direct input to the regulation centre.

In hyperthermia all regulation devices work at it's maximum – not in the state of fever!

This is a very bad sensation for the human body.

Hyperthermia decreases the mental and physiological perfomance dramatically and may lead to death.

All these regulations are very complex and not scientifically known in all details.

To make it even more difficult you have to consider the individual heat tolerance, the amount of body fat , mental and physical workload and environmental factors (e.g. relative humidity, temperature, wind speed, clothing).

Our task is to keep the heat stress as low as possible because of two reasons:
1. to protect the man and his health
2. to keep man's performance performance at it's maximum

II. Mainpart:

In environmental medicine the first goal is to make the work place as adequate to human belongings as possible by technical means.

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

If there are no other technical solutions possible you have to protect the man himself.

The clothing itself conteracts the physiological thermoregulation because sweat is disturbed to evaporate, humidity between skin and clothing is saturated pretty soon; workload is higher with protective clothing (addidional weight, decreased mobility), wind speed cannot reach the skin, etc..

Examples of the influence of wind speed, normal clothing, water vapour restistant clothing are demonstrated.

Several ways of protection clothing are in service:

1. Clothing with heat reflecting surface
   advantage: - protection good
   disadvantage: - protection only for a very limited time
   - evaporation of sweat impossible
   - weight
   - decreased mobility
   - no physiological thermoregulation

2. Cooling jackets with closed bags inside, bags are filled: either with cooled water or carbon dioxide snow
   advantage: good cooling effect
   disadvantage: - weight 5 kg
   - ice may not have direct contact to skin (two reflecting layers inside)
   - no physiological heat regulation
   - limited time

3. Cold bags are worn like a back pack. They have to be protected against the heat from the outside (radiation).
   advantage: - selective cooling of a limited region
   disadvantage: - extra weight (5 kg);
   - surrounding heat (extra weight, mobility)
   - no physiological heat regulation

4. Two layered protection suit with cooled compressed air and heat reflectors
   advantage: - temperature of 100°C possible
   disadvantage: - weight
   - noise
   - very limited mobility;

5. Liquid cooled west (Ef 2000)
   advantage: - good performance, good during flight
   disadvange: - weight for apparatus (15 Kg) on the way to and from the aircraft
   - only apparatus at home base
   - no physiological heat regulation.

III. Progress

If you look at all ways to overcome the problems with heat stress they have one thing in common: they are not using the physiological way of cooling: give the body the possibility to sweat, transport the humidity away and keep an air stream close to the body by much better mobility and indepent of power sources.
This is pretty good realized by a full coverage suit that fulfills all these needs.

Summary:

The thermophysiological regulation of body temperature is partially or completely inhibited by protection suits especially when several qualities of protection are needed.

The result of an insufficient thermophysiological response is heat stress with decreased mental and physical performance of the human being.

To get an idea about the amount of heat stress different physiological values are measured: metabolic rate, heat frequency, mean skin and core temperature, sweat rate, psychological performance tests, loss of energy in W/cm^2, etc. This variety of different datas demonstrats the diffculty to get an exact picture how much heat stress can be tolerated under different circumstances.

Nobody doubts that technical cooling devices are necessary to keep the human performance tolerable and to avoid a collapse that may lead to death:
heat reflecting clothes, cooling jackets filled with water or carbon dioxide snow, two-layered protection suit with cool pressunized air, etc.

The best solution is the natural one:
1. allow the body to sweat and transport the humidity away to keep the environment as dry as possible to avoid a saturation of humidity surrounding the human body.

2. Clothing must not be close to the body in order to allow circulation of air to get rid of the evaporated sweat (chimney-effect).

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GKSS - Advanced Integrated System Concept for Full Protection and Heat Stress Mitigation

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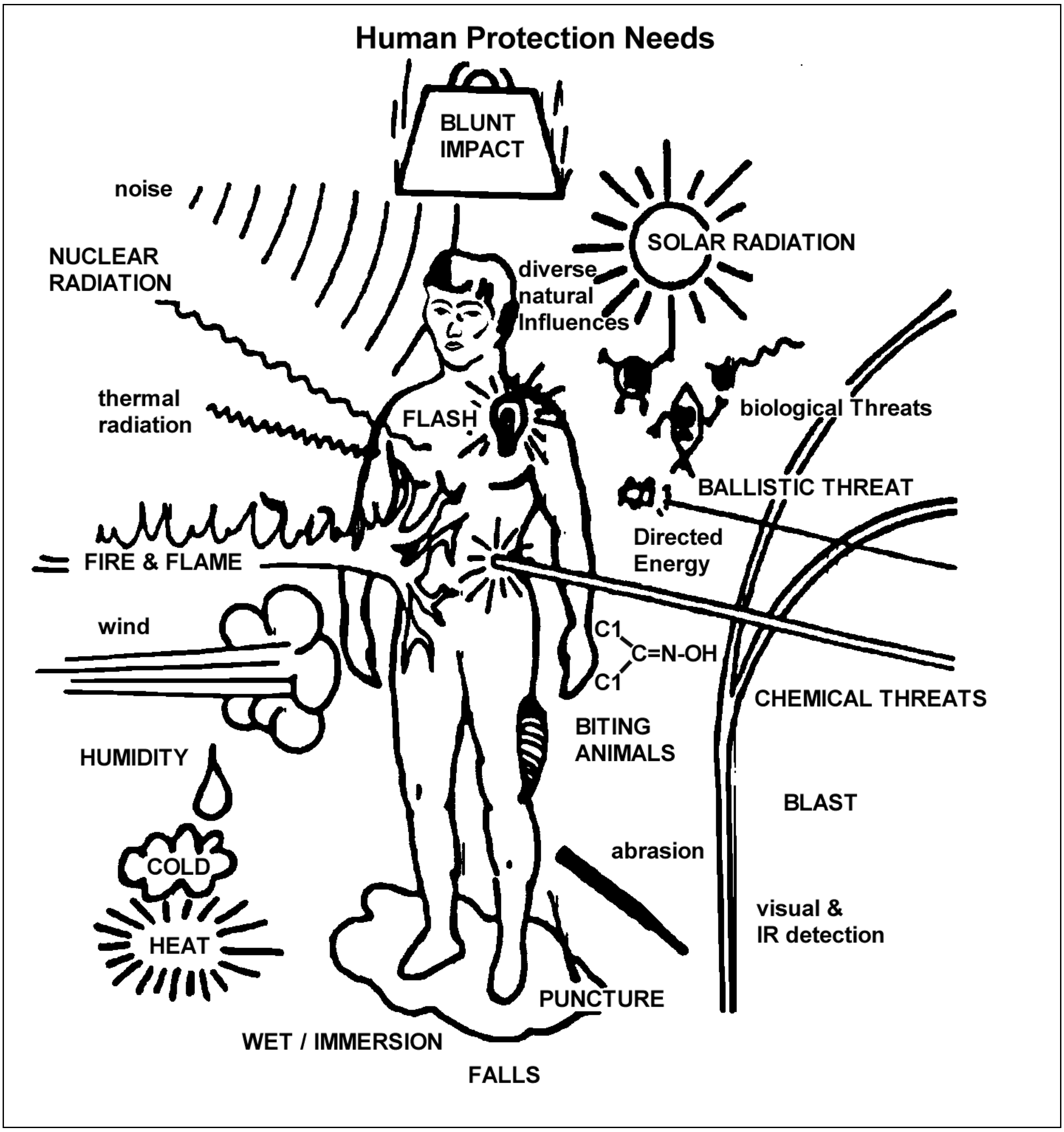
Summary
The increased demand for protection of the human body against external threats and environmental conditions has led to modularity of components for countering these threats and environmental conditions. However, the higher the degree of protection the more negative influence on human performance could be observed. The degradation of human performance situation is caused by multiple layered - onion like - protection garments keeping the body away from natural heat exchange mechanisms. This can be recognized in particular when looking into combat pilot equipment where the result is known as heat stress problem. This degradation is getting even worse when protective garment has to be impermeable as well as semi-permeable. As the operational workload remains it adds to the burden caused by the protective garment resulting in excessive perspiration and finally, leads to dehydration. The alternative approaches to overcome these deficiencies vary from modular components for individual protection needs with no conditioning via liquid conditioning to air cooling solutions. However, the solutions so far have been based on single component optimization with substantial deficits when trying to integrate them. Contrary to these approaches the GKSS – Full Coverage Protection System – approach considers the integrated system concept from the very beginning avoiding the deficiencies encountered with single components for single threat solutions. The GKSS, designed for the most challenging protection needs, comprises helmet, suit and the peripheral components using air ventilation for micro climatization of head and body. The GKSA suit design follows a three layer concept – the outer layer for threat / environment protection, the middle layer for distance keeping (air flow / insulation), and the inner layer for sweat transportation, insulation and limited flame protection. This concept applies in principle for the helmet as well.

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

Introduction

Before addressing the advanced technology applied for heat stress mitigation, the situation of human beings in relation to nature shall be looked at. When man is borne he is naked as many of the creatures. However, when growing up man remains naked while most creatures will build up protective covers like furs, feathers or fish scales.

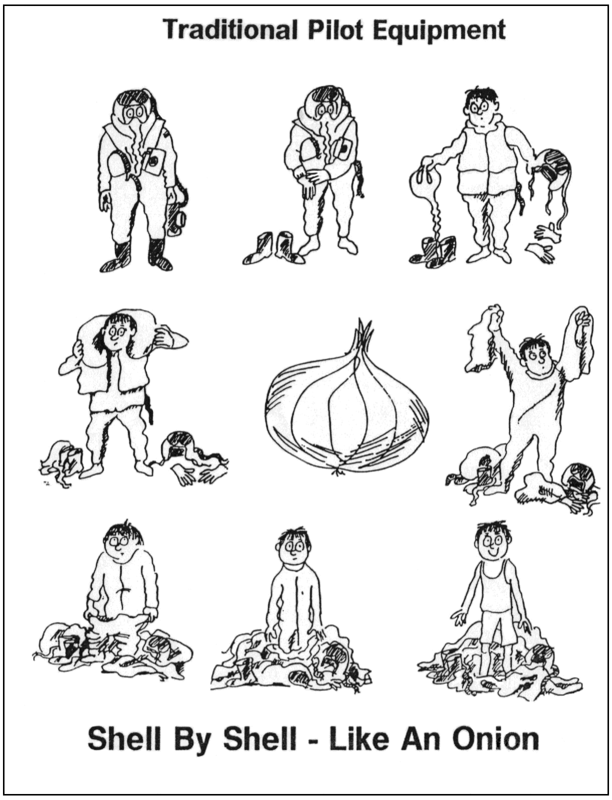


Since man needs protection against rapidly changing environmental conditions - from hot to cold, from sun to rain or snow, or calm to windy conditions - he started covering and protecting himself accordingly by imitating nature using leaves, furs or feathers. And man was the only creature being capable to develop and manufacture protective clothing by means of his hands. But this protection was just against natural environmental conditions. As the evolution of man continued, unfortunately hostile actions with different kind of weapons came into place. Consequently, the priority changed from needs for protection against environmental conditions to protection against threats.

State of today

The above situation is generally relevant to all man working under protection - civil & military - but in particular for all warfighters. For the following considerations, we will refer to the combat fighter pilot as an example with most challenging requirements. During one mission he could encounter extreme environmental conditions as well as all kind of threats – only little difference with peace time flying or combat operation. In order to meet these needs and maintain a certain kind of flexibility the most popular protection concept applied is the single component / single threat / environment approach with optimized protection features for special environments or threats.

From the pilots' standpoint this situation is shown below.



However, the requirement to simultaneously wear impermeable, semi-permeable or permeable protection components generated new problems: heat stress on the one side and incompatibility of the components on the other side. When trying to perform system integration based on these single components, it usually is considered at the very end of a development. The result is very often: It is either too late for integration or worse - not even feasible at all. Example: To our knowledge, there is no integrated protection against CB and cold water immersion available for fighter pilots - at any service worldwide!

Does this indicate the limit of the single component / single threat approach - onion like - for life support equipment?

New Technical Approach: Integrated System

To our understanding, integrated life support systems offer a way to overcome the discrepancies of single component / single threat systems.

If we are right - one may ask: Why have they not been introduced yet?

There are several reasons for this:

- The need for a high degree of integration for protection garments was not prevailing in the past - but latest experiences in hostile engagements revealed this necessity.

- Since integrated garments include multiple protective functions simultaneously they might look bulky on the first glance and they might not be worn on all occasions – therefore they are often lacking acceptance by pilots under daily (peacetime) operation.

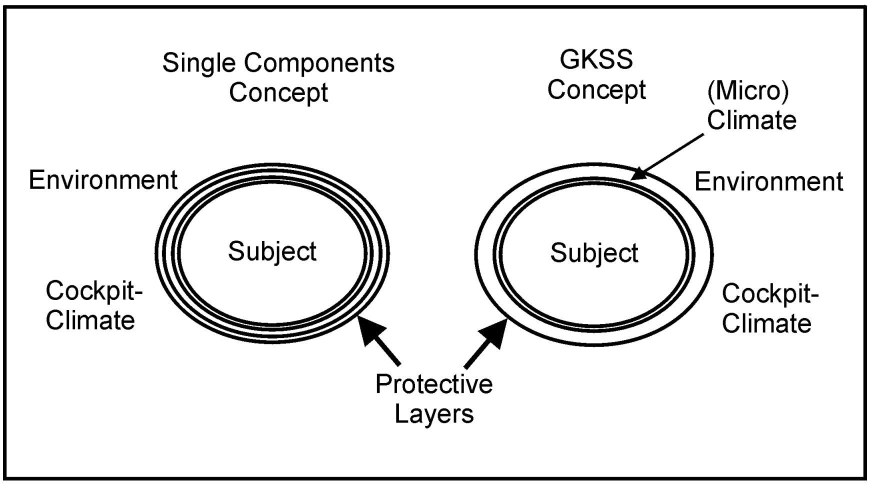
- Missing technologies and suitable materials.

- Logistics: Improvements of single components / systems are at lower cost - replacing only one component at a time (but the improvement as well is limited to even this component). On the other hand introducing an integrated system offers a major step - but would replace a number of components and is more costly therefore.

- But the major reason of all seems us to be experience - the experience with the limits of the single component approach for single threat / environmental conditions.
  These limits are well understood amongst the services, the engineers and scientists now
  - otherwise we all would not have met here at this dedicated symposium!

Our involvement in different fields of application – spacecraft and combat aircraft – and our experience with limitations of the single components approach for single environments / threats led us to initiate the advanced integrated systems approach for full protection and heat stress mitigation (GKSS). This system concept approach means - instead of looking for improvements of individual components - to consider the overall requirements and to tailor the system, all its subsystems and components to these needs. The result achieved is presented today as the GKSS – the Full Coverage Protection System. For the purpose of introducing the GKSS, it is focused on the most challenging application case - jet fighter pilots and their burdens during combat operation.

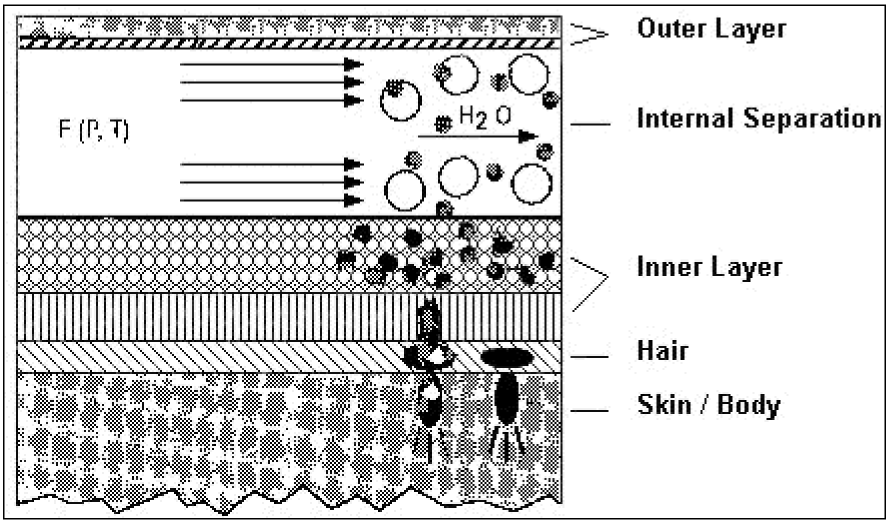
How did we proceed? Right from the beginning it was quite clear that the idea of integrating all protective components / measures between the pilot and the (hostile) environment simultaneously, would automatically insulate the pilot to a peak accumulation of heat stress. Since this was strictly to be avoided by the integrated system, our first step was to turn this design procedure upside down:



Looking at the single components concept, the protective layers are next to the pilot, thus separating / insulating him from the (cockpit) climate and <u>causing heat stress</u>, while the GKSS allocates a micro climate next to the body surface, <u>thus preventing heat stress</u> and keeps the protective layers outside / apart from the pilot.

Now, after the first step was done by "rearranging" the layers, thus incorporating the (micro) climate zone, the second step was how to implement this technically: This was achieved by what is the principle of the GKSA: comprising three special layers tailored to customer needs and with dedicated functions:

1) an inner layer,
2) a middle layer, and
3) an outer layer.



1) The inner layer, which is similar to underwear, is designed for three functions:

- Primarily it supports the human thermoregulatory system to transport heat and to evaporate humidity from the body towards the middle layer. These processes are paramount prerequisites for heat stress mitigation.

- As a second task the inner layer functions as an insulation which applies in particular in cold or when immersed in cold water. Therefore different materials may be used for extreme insulation purposes, however, the functionality for support of the human thermoregulatory system is not compromised.

- Fire protection by flame retardant material, adding to the fire protection of the outer layer.

2) The middle layer is an internal separation consisting of a flexible, air permeable material, keeping a defined distance between the inner and outer layer. This way, an internal separation is generated, which extends around the body surface and is designed for multiple functions:

- Flow duct for circulating air around the body surface!
  This is the key issue of the GKSS concept and the highlight of our presentation on heat stress mitigation.
  What happens? An air flow ventilating through the system, when passing through the separation, picks up heat and – most essential – humidity / perspiration of the body, which was transported by the inner layer material to this air flow.
  Only this effect, which we call “Micro Climate Zone”, allows the body to maintain it’s natural thermophysiological mechanisms for dry and evaporative cooling – even under workload, and as if it was not encapsulated by all the protective layers outside!
  This is our way of heat stress mitigation under protection and workload, in principle. It is obvious, that this way offers further potential: Depending on operational requirements and working conditions, the air flow in the separation can be matched by means of lower or higher flow rate (chill effect), it may be just ambient air or conditioned air by cooling or heating it. For this purpose, the third following presentation "Air Ventilated Heating and Cooling based on Zeolite Technology" will provide you information about a new and promising technology, which is used to improve our artificial Micro Climate Zone inside the GKSS.

- The air layer contained in the separation provides for insulation against external heat, including flames, radiation and external cold, including cold water. This is true even under emergency conditions, when no air flow is available and the internal air layer is in rest.

- The air volume, contained in the internal separation provides lift in case of water immersion under emergency conditions.
  Further to this, the particular distribution of this air volume in the separation layer around the body provides a particular lift distribution while immersed, with other words: flotation attitude and flotation stability.

  All these functions are interrelated by the fact that they all are depending on the thickness and distribution of mentioned spacer material around the body. Therefore the design of the middle layer requires a sensitive and careful trade-off between ventilation, insulation, and flotation needs as well as bulkiness / mobility considerations. For instance the separation is designed with thicker distance material in those areas where compression could occur, e.g. under external forces or body weight such as in the buttocks, the back area and the areas where harnesses could hinder a free air flow. Where these requirements are less stringent the distance material will be thinner for better mobility.

3) The design of the outer layer is tailored to meet the various operational protective functions. However, the minimal requirement for the outer layer is to be air tight with respect to the internal air flow and it should fit to the individual body in order to avoid excessive space between the layers which will cause the air not to circulate properly through the internal separation. Also, the airflow may not be too high as it will cause a storm inside and balloon the system like the Michelin man, further it might harm the individual in the mid and long term.

   The material of the suit’s outer layer presented today meets the general requirements for pilot equipment. Particularly it is designed to be resistant against

   - war agents like Mustard, Sarin, Soman, in all phases liquid, vapor, gas,
   - fire and flames,
   - POL,
   - wear and tear,
   - immersion;
   - blast,
   - e.t.c.

In addition to these three functional layers the system comprises an air distribution system inside the suit. This receives the air flow from an external module supplying (filtered) ambient or conditioned air and leads it to the primary human heat exchange surfaces. These surfaces - which are legs, arms, and head - have been carefully investigated and verified in close cooperation with the expertise of the GAF IAM. We can assume, that IAM harmonized with our mothers, because they already applied this knowledge when we had fever, she used to cool our wrists, calves and forehead - but never the chest (body core). So, we survived without pneumonia and got the opportunity to design the GKSS accordingly, leading the cool air flow to enter the internal separation at the ankles (and / or wrists, depending on the design) and head. From the extremities, the air flow distributes to the body center, following the lowest back pressure through the separation, picking up heat and perspiration generated according to the individual’s workload and external loads and finally exits at the outlet valves.

Summarizing, the GKSS concept is characterized by

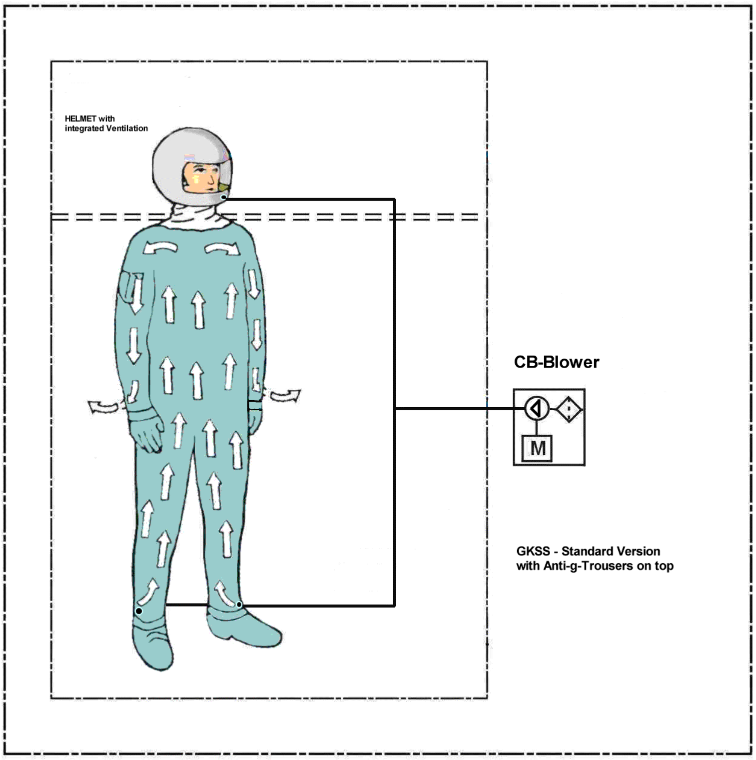
- integrating various protective functions in a total of three layers (including underwear), and leaving it open to add more protective measures on the outside, e.g. parachute, ballistic vest, survival vest, etc.

- incorporating a Micro Climate Zone close to the body for heat stress mitigation.

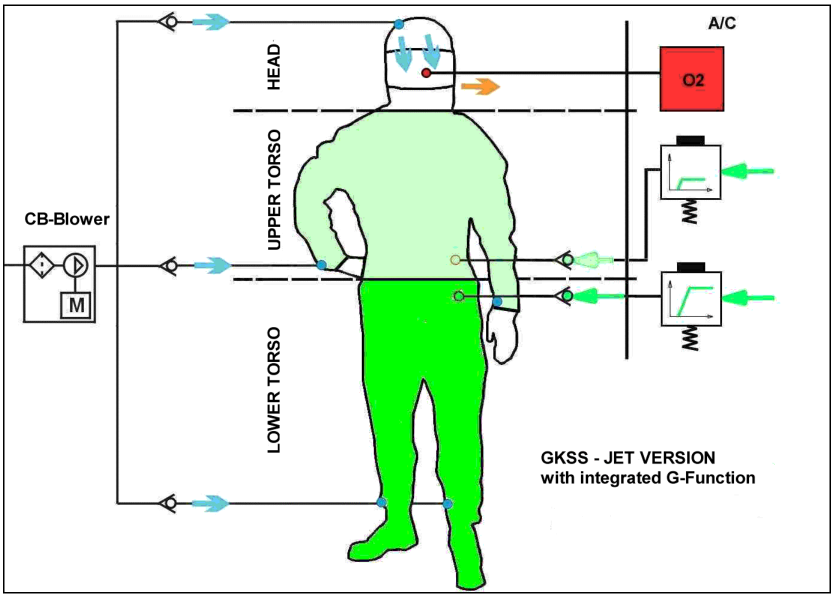
But - since we selected the combat fighter pilot Life Support System as the most challenging application to describe the GKSS principles and potential, you might be asking how to inhibit g-protection?

This has been resolved in two ways:

a) The standard GKSA configuration as just described in combination with the conventional in-service anti-g-trousers on top of the suit can provide g-protection for fighter bomber aircraft such as TORNADO without change of aircraft interfaces.



b) For g-levels of high agility fighter combat aircraft a particular GKSA - Jet configuration was designed: The micro-climate zone around the body was divided by an impermeable membrane into an upper and a lower torso regime allowing for different pressure levels of the air flow. This configuration, however, would require modification of the aircraft interface or is available for integration into new aircraft.



Both configurations incorporating g-protection in different ways are including all other protective functions described before as well as the particular heat stress mitigation provided simultaneously. Detailed test results on both configurations will be given during the following three presentations.

The application tracks chosen for the GKSS are:

- General military multi purpose / multi function system, e.g. tactical aircraft, helicopter, transport aircraft, tanks, vehicles, infantry, etc.
- Special military multi purpose / multi function system for tactical aircraft with high agility
- Tailored commercial function system, e.g. for fire fighters, chemical fighters, nuclear power plants, racing cars, etc.

Historical Development

The concept to realize a close to the body micro climatization goes back to the year 1985, when it was presented to the German MoD. 1986 followed the development and manufacturing of a ventilated prototype helmet without mask, while in 1987 initial testing and ergonomic investigations have been conducted in close collaboration with the German Air Force Institute for Aeronautical Medicine IAM. Based on these results, the design and manufacturing of the first Full Coverage Protection Suit including g-function followed in 1987.

After simulation of the thermal conditions with the suit, first evaluations were conducted by French Pilots of the European Space Program as well as by the RAF - SAM (1989/1990). Also in 1990 pre-tests for air conditioning (GAF IAM) and g-function testing (USAFB Brooks, 1991) were carried out. Still in 1991 a test series for air conditioning was performed, followed by the verification of thermal conditions. Multiple presentations in 1992 and 1993 included GAF Armament Directorate, General Flight Safety, Zvezda, and SAFE Europe. Late in 1993 centrifuge testing was initiated at GAF IAM, which was continued with improved GKSA – Jet versions up to 2000.

In 2000 GAF continued g-testing and concentrated investigations on compatibility and integration possibilities between the new FAS helmet (flight helmet with NBC protection) and the GKSA helicopter version for TORNADO. Additionally, compatibility investigations have been conducted for the C160 TRANSALL transport aircraft and the new TIGER helicopter. Since one of the major requirements was flying over sea, combined FAS / GKSA immersion testing in the pool and open sea and cold water tests in the climatic chamber have been carried out in 2001. G-protection by using the standard GKSA suit and conventional in service anti-g trousers was tested in 2001 by GAF IAM.

In parallel to the efforts of GAF, extensive work based on the GKSS concept has been conducted in the USA. In 1995 the GKSA System was presented to USAF, at AFB Brooks and to USN at NAWC Warminster. In1997 USNAWC initiated the Helicopter Aircrew Integrated Life Support System (HAILSS) Program comprising a full helicopter pilot ensemble for operation under CB conditions over water. Industry conducted system performance tests and material qualification tests including fire tests on the Pyroman and CB tests. In parallel USN conducted thermal, Clo, buoyancy, CB and material testing and aircraft integration, cumulating in USN plans to perform flight verification testing on helicopters in the second half of 2001.

GKSS Status and Test Results

Having described the technical GKSS concept and our long way learning from mother nature how to implement it, it's now time to talk about test results in detail.

It is a particular pleasure to us, that two competent institutions, conducting test efforts in parallel over years, will report their respective results, conclusions and - hopefully - perspectives. This will be given from the side of USN by Dr. Förster and from side of GAF by Col Dr. Knöfel / Col Dr. Welsch / their representatives as well as from the BWB, Mr Fusz, in the following two presentations.

In addition to that, the mentioned innovative Zeolite technology, which is applied when cooling is becoming more stringent, will be presented thereafter by a Dr. Schmidt of Zeo-Tech GmbH.

Results and Conclusions:

Testing at GAF, USN and ourselves established the evidence - from our point of view - for the GKSS concept being a promising and feasible solution to integrate paramount functions for heat stress mitigation and for protection into one system - which can be tailored to particular operational needs. GKSS is clearly an innovative concept, and - as new things always do - it may create concern. But, our concern should better concentrate on the conventional equipment and it's limitations. To overcome these, a new system has to be different and thus novel. As you will see from the following test results the GKSS concept has a big potential for any man under workload requiring simultaneous protection - military as well as commercial.

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Design Concept and Test Results of Full Coverage Protection Suit (GKSA)

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Introduction:

About 10 years ago the GAF started experimenting with a full Coverage Protection suit.
The idea was 1. to come along with the bulkiness of several protection suits
2. to find a physiological way of thermoregulation
The secret of the suit is the air flow inside the suit and the distance layer that guarantees a constant flow in all regions. At the same time the trapped air in that distance layer isolates perfectly and gives a buoyancy that makes the suit also perfect for water inmersion.

Main part:

Test results are demonstrated at high temperature (40°C) in the climate control chamber, also at low temperatures dry (+1°C) and wet (+7°C) in comparison with special protection suits.
Sensors are used for skin temperature (including head, fingers, feet), mean skin temperature (Ramanathan), core temperature, humidity between the underware and the suit, blood pressure and heart rate. Psychological tests were carried out every 30 minutes before, during and after the test, also individual opinion how the chosen climate is tolerated according to SAM 136, treadmill test every 30 minutes (1W/kg/body weight). Equipment was weighted before and after the test, urin was examined, blood samples were taken and stress hormones out of saliva were determined 4x during the test.
For the ability as an water immersion suit competitve tests were carried out at the school of sea survival in an indoor pool as well as on the open sea.
For the ability as an BC-protection suit material tests were carried out in the German „BC-Test Centre“ and in the US according to their regulations, also flame retardency test.

Paper presented at the RTO HFM Symposium on “Blowing Hot and Cold: Protecting Against Climatic Extremes”, held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

Conclusion:

With this suit we have a system that allowes almost normal physiological thermoregulation because of its principle of air flow.
The protection needed – also in combination – can be produced according to the task the customer looks for - from race car driving over flight envelope to civil use at heat working places, fire brigade, chemical workers and so on. The principle of the suit is an air stream close to the body that allowes normal evaporation. Humidity can be transported away.
For the flying personnel it means that they stay fit to fly the aircraft at it´s and their maximum performance throughout the mission.

Summary:

The optimum to regulate the temperature and humidity while wearing protective clothing is to be – in the applied technique – as close as possible to the physiological way of thermoregulation.

The Full Coverage Protection suit is very close to this aim, several tests under high g, water immersion, cold water, cold air, heat and BC show very promissing results.

Air Ventilated Heating and Cooling Based on Zeolite Technology

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Summary

A promising technology identified and ready to be used for a man mounted micro-climatization system (MiCS) is the zeolite vacuum-adsorption technology. This technology uses the non-hazardous, non-explosive, non-toxic and environmental friendly working pair zeolite and water. Zeolites are crystalline, porous aluminum-silicates with well-defined pore structures. The most important property of the zeolite is its ability for adsorption of water in a reversible process. The adsorption / desorption technology inherently provides for storage of energy, to be used either for heating and cooling. Besides moving the air flow heat is the only energy input. The core module of the MiCS is a conditioning unit consisting of the zeolite-sorber and the water reservoir interconnected by a control valve. Sorber and reservoir are designed as heat exchangers to provide either cooling or heating to the climate air flow. The technology has been successfully used by US Navy within the HAILSS Program with its APACS (Advanced Portable Air Conditioning System). The recent flight model configuration provides a cooling power of about 50 Watts for more than 2.5 hours to the conditioned air flow. The heating performance of such a system is in the same power range. The zeolite/water adsorption technology offers manifold applications in various domains of cooling, heating, and dehumidification.

1. Introduction

Advanced protective ensembles integrating life support functions such as GKSS (see paper of Just, J. et al.) rely on air supply, to be distributed to the system's interior climatization zones and to the respirator by means of an air blower. Depending on the prevailing environmental conditions, the air flow has to be conditioned for cooling and heating - which transforms the blower into a Climatization System. The major challenge is, to have such a system independent of external power supply and simultaneously man mounted at smallest weight and size. The realization of an autonomous Micro-Climatization System integrated with a GKSS will grant a close to the body climatization. A promising technology identified and ready to be used for a man mounted micro-climatization system (MiCS) is the zeolite vacuum-adsorption technology.

2. Zeolite/Water Adsorption Technology

The name Zeolite is a general term for minerals which consist of crystalline metal-alumo-silicates with a large internal surface area of up to 1,000 m^2/g, strong electrostatic fields in the crystal lattice and with a volumetric density of about 0.8 kg/dm^3. The word zeolite is of Greek origin and means »boiling stone« which describes the effect which is to be seen if water is poured over dry zeolite. In 1925 the process of water and methanol separation using zeolites was observed for the first time. And due to this separation action (sieve action) the name »molecular sieve« was later attributed to zeolites. Zeolites are non-poisonous, inflammable, are naturally available in abundance and therefore compatible with the environment. More than 40 natural and over 100 synthetic zeolites are known. The most important property of a number of zeolites is their ability for reversible adsorption of water.

Even after several thousand adsorption/desorption cycles the structural changes of the crystal lattice are insignificant if the process parameters pressure and temperature do not exceed certain limits. – The application diversity of zeolites is tremendous: They are applied as molecular sieves, as adsorbents, as catalyst in cracking of hydrocarbons in the petro-chemical industry, as filler component in paper production and as ion exchange material in detergents. Currently the chemical industry produces more than 1.4 million tons of synthetic zeolite annually, and it can be expected that the world wide demand and consequently the production will further increase. The price, e.g. for laundry detergent zeolite is between 0.5 and 2.00 DM/kg, depending on the type and consistency of material delivered. The price for specialized zeolites is higher.

The primary modules of zeolites are tetrahedrons consisting of four oxygen anions and one centrally positioned silicon or aluminum cation. Zeolites are classified according to the various tetrahedral frameworks formed by these basic modules. The structure of the synthetic zeolites of types A, X and Y which have gained importance in industrial processes, are shown in the Figure 1.

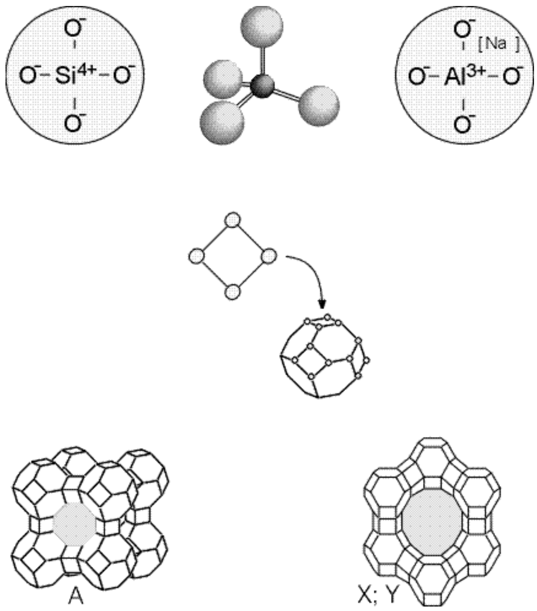

Figure 1: Structure of Zeolite

The aluminum and silicon atoms are positioned at the junctions while the oxygen atoms form the bridges between the tetrahedrons. The difference in electro-chemical charges between the aluminum and silicon atoms per one aluminum atom results in a non-compensated negative charge. The balance is restored by metal cations which occupy preferred positions. Because of the strong local electrical dipole moment in the lattice framework, zeolites adsorb all polar and non-polar molecules that fit into their specific framework. This adsorption process is accompanied by release of heat, the »heat of adsorption«. Theoretical and experimental studies have determined quantitative heat of adsorption values for zeolite based thermal processes.

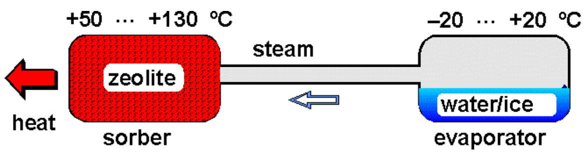

Figure 2: Adsorption Phase

In contrast to absorbing techniques we have in the case of zeolite a non-chemical but reversible physical process (adsorption) taking place: This crystalline mineral has the very special property of attracting and adsorbing water vapour in its crystal structure while at the same time releasing heat. If the adsorption process takes place in air-free and vacuum-tight vessels, then the adsorption of water

vapour proceeds very rapidly. Due to the heat of evaporation, the water in the evaporator cools down and freezes (s. Fig. 2). The ice produced in the evaporator can then be utilized for cooling and air conditioning purposes, while simultaneously heat is produced in the other compartment of the equipment, in the zeolite adsorber zone. If a valve is placed in between the two vessels (evaporator and adsorber) then the adsorption process can be interrupted for an arbitrary period of time without loss of energy. The process of adsorption continues until the zeolite is fully saturated with water.

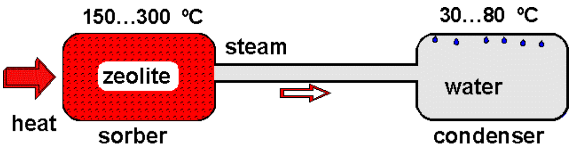

Figure 3: Desorption Phase

In a consecutive phase the zeolite can be regenerated (s. Fig. 3) by applying heat to the zeolite: the water is now desorbed in gaseous form from the zeolite. By removing heat in the evaporator vessel, the water is condensed and collected. If the valve between the two vessels is closed, the expended energy for charging is stored and can be retrieved after an arbitrary period of time. An almost continuous production of cooling power can be accomplished if two ore more sorption devices are operated in a phase shifted manner. The desorption of water can be powered by electrical heaters or, in a more energy-efficient system, with heat produced in combustion systems or even solar collectors. If this system is applied in dual use mode for heating as well as cooling in parallel, the overall net effect as shown in Fig. 4 amounts to 160 % of the expended input heat (100 %), provided as heat (130 %) and cooling power (30 %).

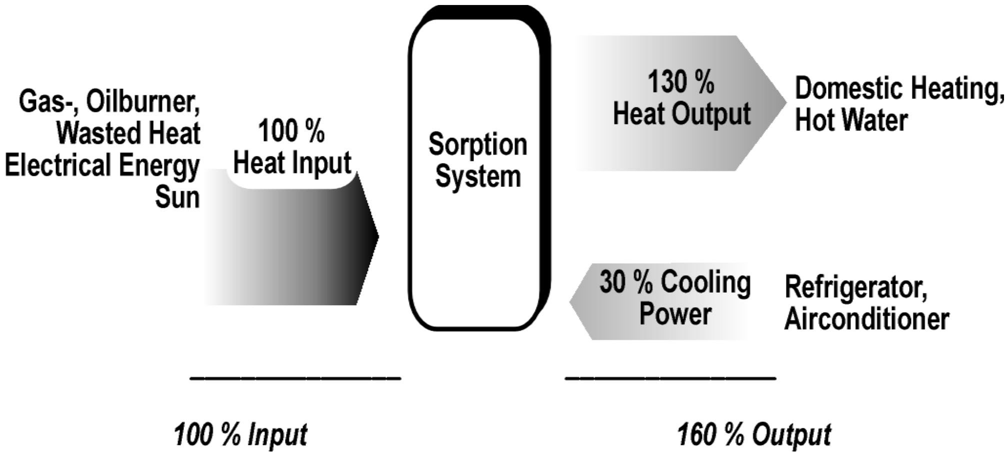

Figure 4: Energy Flow Diagram

Even with electrical heating, a sorption system provides considerable energy savings and a corresponding reduction of carbon dioxide production. With other input heat sources the energy saving potential is much higher with corresponding environmental benefits. Even the single use mode, utilizing only heating or only cooling power, is comparable or better (with respect to energy utilization) than any conventional technology. It is important to note that zeolite is very environmental friendly, it is non-toxic, non-hazardous, non-explosive and has no global warming and no ozone depletion potential. Further advantages of a zeolite system is the little need for maintenance (virtually no moving parts) and the unlimited lifetime of zeolite.

3. The Micro Climatization System (MiCS)

The challenge of the development of MiCS was the provision of conditioned air flow for the generation of a micro climate inside NBC protection suit e.g. the full HAILSS ensemble (helmet, respirator, suit). Due to external requirements, e.g. in an aircraft where no access to aircraft systems or modifications are allowed and different operational environments are existent, the need for a man mounted portable air conditioning system evolved. The anticipation is, that aircrews using the new system will benefit from its performance to lower the heat stress during their missions in hot environments. The performance of MiCS is independent of the attitude in which it operates and the inherent zeolite adsorption technology needs no moving parts compared to compressor technology.

System description

The MiCS performance requirements for the APACS Flight Model (FM) have been set up to:

- provide approx. 250 l/min of air at least 2 hours:
- cool ambient air of 35 °C (95°F) at relative humidity below 50 % by approx. 8 ± 1 °C for a minimum time period of 2 hours.
- total weight of the system < 6 kg

The main task of APACS FM is to provide heat stress protection. This will be realised with an aviator cooling in the HAILSS by blowing cooled air over all body surfaces including contact surfaces, thereby improving operational effectiveness and enhancing flight safety. A further very important point is that the APACS FM will not compromise on any of the protection functions of the HAILSS: This will be achieved by proper integration with HAILSS and by establishing its own APACS protection measures against environmental threats.

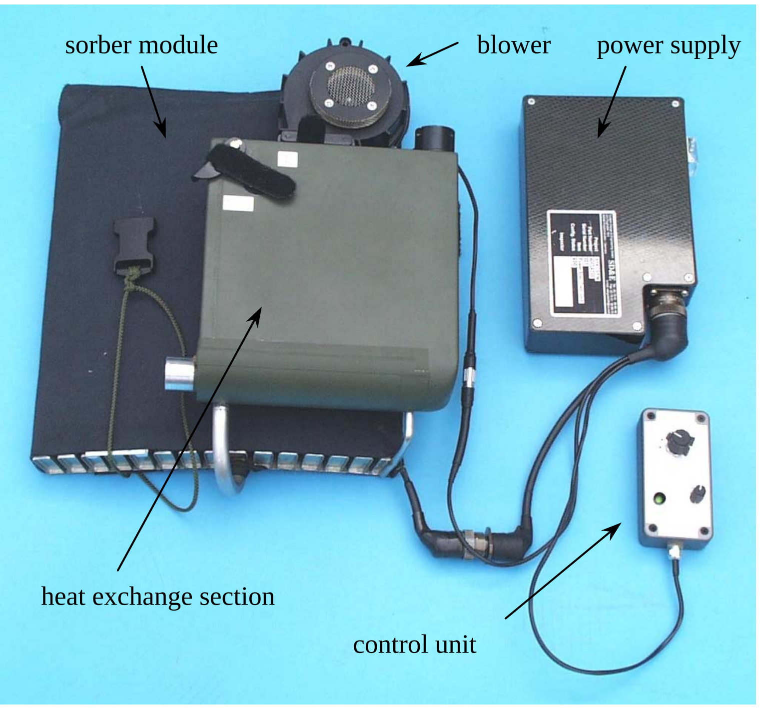

Figure 5: The APACS FM with Integrated Modules

The operation of APACS will be independent of the aircraft systems. This will be achieved by its own power supply and regenerative heat capacity technologies. The benefits are reducing the number of helicopter interfaces, eliminating the requirement for additional air on board and reducing the cockpit air conditioning requirement as well as eliminating additional purging air for CB-protection and saving electrical energy. Further important is that the maintenance and acquisition costs are reduced

and the use of the APACS outside the aircraft as well as in pre- / postflights, ground and in emergency conditions is possible without restrictions. Due to the requirements arising for flight testing, the design of the APACS FM had to consider a high degree of integration issues which has led to the configuration with modules as shown in Figure 5:

Conditioning Module

The design of this module as the core of the APACS FM unit (s. Fig. 5 and 6) consists of the heat exchange section with control valve and a solid housing which also provides the functions of air inlet for the heat exchange section and air distribution for suit, helmet and respirator. The sorber section together with a flexible case acts as sorber module for cooling (ventilation) and protection purposes.

The principle of the conditioning module is based on Zeolite technology as described above which allows the conditioning of air, i.e. for the APACS FM to provide cooling for a minimum of 250 l/min with a temperature drop of $\Delta T = 8 \pm 1$ K for approx. 2 hours.

The interconnected and evacuated heat exchange and sorber sections are made of stainless steel with a completely new exterior design and interior configuration. The exterior design as well as the interior configuration have been chosen in order to meet the customer’s dimensional requirements and to optimise the access to the zeolite energy.

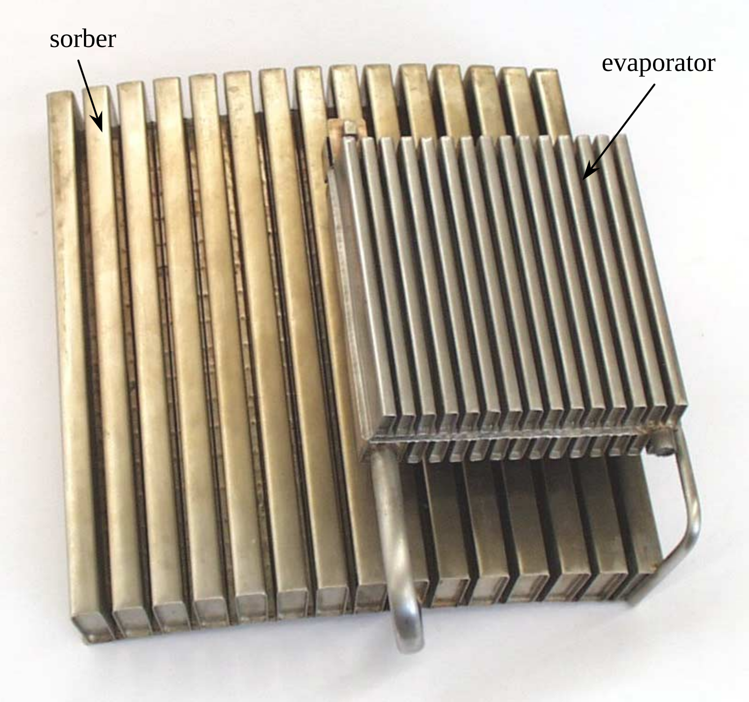

Figure 6. Conditioning Module with Heat Exchange and Sorber Section

Heat Exchange Section

The heat exchange section is the cold section of the conditioning module for cooling the external air flow while inside the section the water evaporation process occurs. It is designed with a structure in the longitudinal direction with integrated ribs which are filled with a water absorbing filling. The lower section incorporates a manual control valve. After joining both sections, the junction forms the vapour channel. After the control valve has been opened the channel allows the water vapor to be either transferred via the connecting tube to the sorber section (when adsorbing) or vice versa (when desorbing). A spring shuts off the conical control valve when the control lever is in the “CLOSED” position. The solid housing (s. Fig. 7) around the heat exchange section is made of a sandwich structure made of Carbon - Glass Fiber. It functions as a protection cover (housing) for the heat exchange section and reception provision for the manual control lever as well as air inlet with

attachment provision for the ventilation module. It further provides the air distribution with outlets for the suit and receptacles for the connectors to the helmet and the respirator.

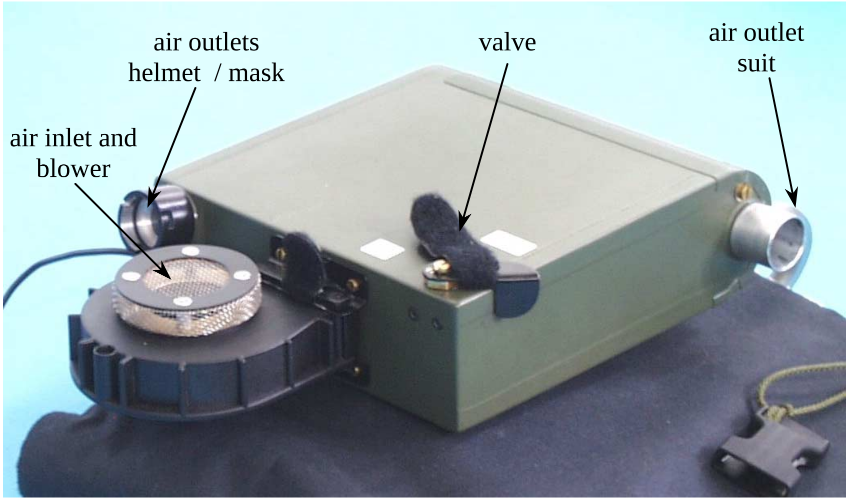

Figure:7: Heat Exchange Section with Housing

Heat Exchange Section with Housing

The air flow enters over the integrated air inlet module on top of the housing. The heat capacity of the inlet air will be exchanged along the distance via the ribs around the rectangular water tank. After the air has been cooled down, it leaves via the integrated air distribution to the outlets for the suit and respirator / helmet. When opening the two position control valve (off / on) the heat exchange section and the sorber section will be connected. This will activate the physical reaction of the zeolite (water vapour) and will cause the heat exchanger to cool down the surrounding air flow inside the housing. After passing the whole heat exchange section the cooled air will be ducted on the air distribution outlets.

Sorber Module

For the ventilation of the Sorber module a flexible case made of Nomex Delta T/A is used, and a provision for forming an air channel and reception of two ventilation blowers and a connector to the power supply module. The Power supply module is consisting of a case with e.g. a high power Lithium-Ion battery, a master power switch, an interface board with the ASIC for controlling the blower of the ventilation module.

Attachment to AIRSAVE Vest

The attachment of APACS FM to the AIRSAVE vest is conducted by means of attachment straps with snap fasteners which will be slid into the vest structure.The APACS FM itself will be positioned with the sorber section underneath the AIRSAVE vest while the heat exchange section will remain on the outside.The final arrangement is shown in Fig. 8.

Figure 8: APACS FM Arrangement on AIRSAVE Vest

Regeneration Unit

A very important requirement for the APACS FM is that the system is reusable with a lifetime of at least 10 years. As pointed out above, zeolite can be periodically regenerated with a virtually unlimited lifetime as long as the applied temperature and pressure do not exceed certain limits. For the APACS FM a regeneration unit has been specially designed. The regeneration unit is not an integral part of the APACS but an independent device for desorption (regeneration) of the conditioning module. The unit consists of the ventilation tunnel which is designed to house the sorber section of the conditioning module and also to distribute the hot air provided by the heat gun and to desorb (regenerate) the zeolite. The heat gun is operated electrically (AC 110V/220V). The regeneration process will take about 2.5 hours at a temperature of 350° C (662° F) for complete regeneration (drying) of the zeolite.

4. Performance of the APACS FM

A typical experiment with the APACS FM is shown in Fig. 9. After starting the ventilation and cooling at t = 0 of the system integrated in a GKSS at t = 10 min a constant temperature drop of approx. 10 K between the ambient air and the air ventilated to the helmet (head) and body (suit) is established for about 160 min. The mean cooling power of the system during this time period can be calculated from the data shown in the viewgraph:

$P_{cooling} = Q\ (t = 170\ \text{min})/\Delta t = 500\ \text{kJ}/160\ \text{min} = 52\ \text{W}$

For safety considerations it is important to note that even after 200 minutes running time of the system a temperature difference between the ambient and inside the suit/helmet of 8 K is perpetuated. This significant additional cooling energy can be used, e. g. in a case of emergency, where the running time of the APACS FM has to be significantly extended.

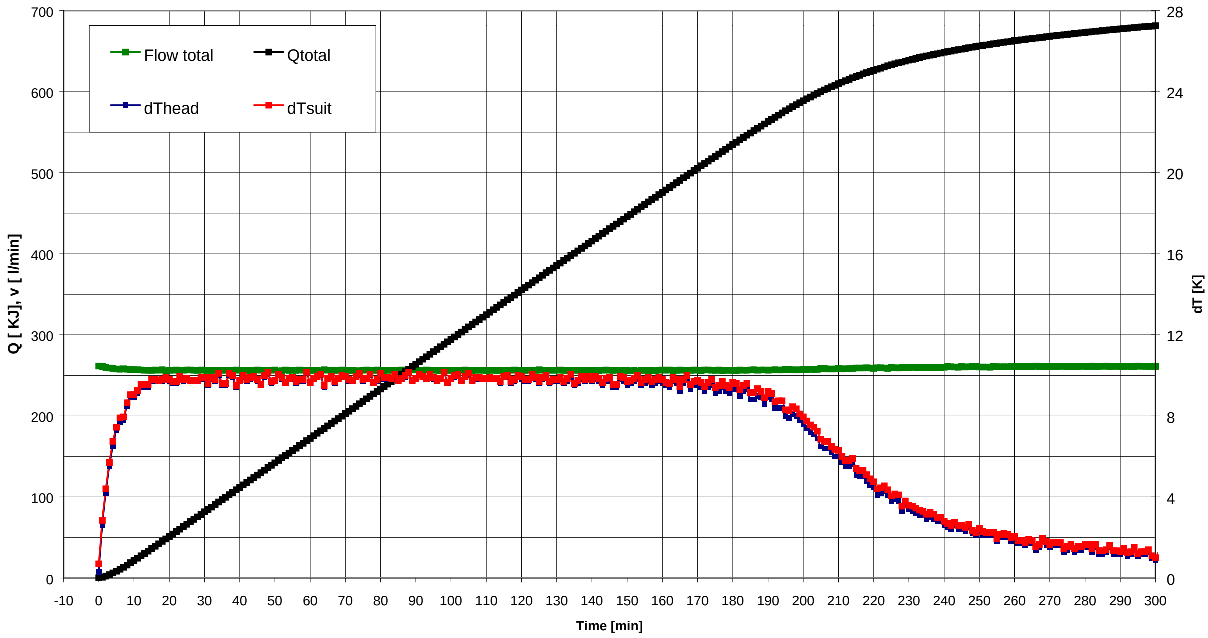

Figure 9: Typical measurement with the APACS FM. Ventilation and cooling of a GKSS at a total flow rate of ca. 250 l/min and an ambient temperature of 35 °C (95 °F) and 40% r. h.

Personnel located in hot climates often suffer severe cognitive and/or physical performance degradation or injury while performing military tasks due to extended exposure to very high environmental temperatures. The application of man-mounted cooling units as the APACS FM, will extend individual tolerance to environmental conditions without affecting task performance. To test the full cooling capacity installed in the APACS FM the internal vapour valve had been set to a full open position. Figure 10 shows the simulation of a so-called “helicopter start” in a clime chamber at high ambient temperature of 55 °C (131 °F) and relative humidity well below 30 %, e. g. typical for special desert missions. The air flow rate through the APACS FM was adjusted to (280 – 290) l/min.

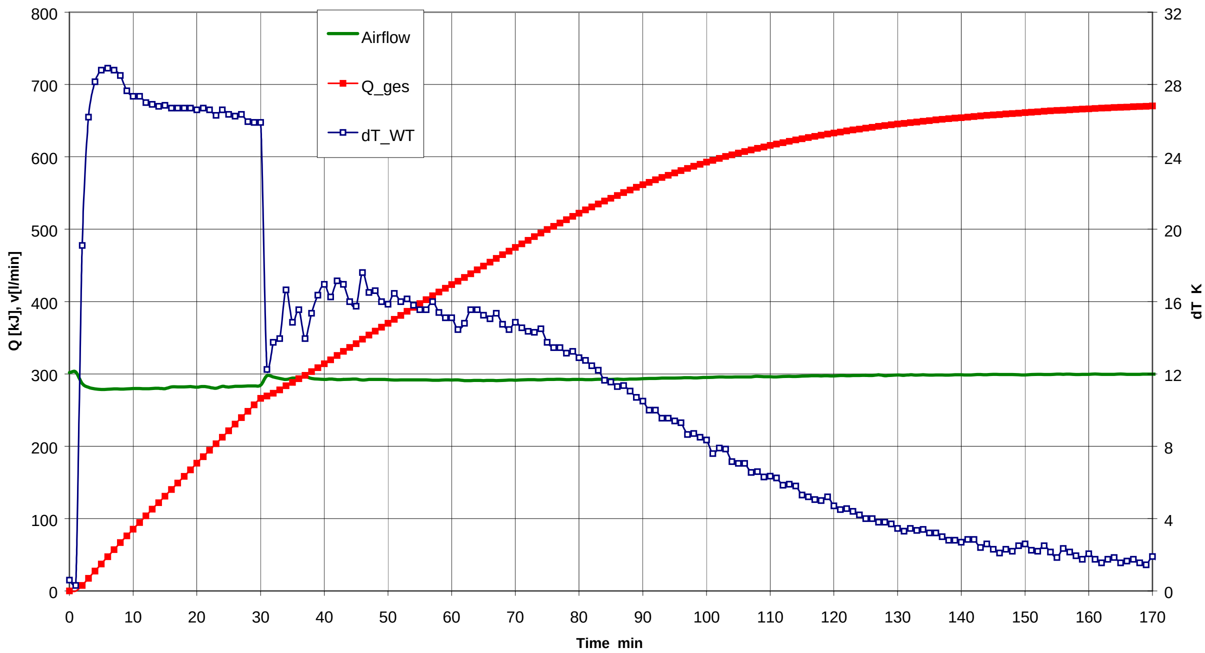

Figure 10: Clime chamber simulation of a “helicopter take-off”-procedure and pilots using the APACS FM in connection with a GKSS..

The procedure was: From t = 0 to 30 min there were high ambient temperature conditions of 55 °C (helicopter waiting for take-off). Afterwards the helicopter takes off and the ambient temperature drops to 35 °C.
It is important to note that during the stand-by period at high ambient temperature of 55°C the APACS FM generated a temperature difference between suit/helmet and ambient of $\Delta T = (26 – 28)$ K with a corresponding cooling power of about 160 W! The explanation for this behaviour of the APACS FM is the higher pressure inside the evaporator at a higher ambient temperature. The water vapour flow to the adsorber unit is enhanced compared to the lower temperature situation. Therefore the cooling power of the system is higher at higher ambient temperatures.
Operating an APACS FM, the user benefits from a temperature of approx. 28 °C (82 °F) inside the suit and helmet even at these high ambient temperature. After take off the cooling power of the APACS FM falls down to about 87 W without further manual adjustment. The resulting temperature inside the helmet and suit is approx. 21 °C (70 °F).

In cases where the ambient temperature is well below 35 °C (95 °F), the resulting temperature difference between inside the suit/helmet and the ambient diminish and the resulting overall mission time increases respectively.

5. Outlook

In future advanced versions of the APACS FM, a manually adjustable cooling power of the system will be realised in order to enhance the complacency of the operators especially under variable ambient conditions and in situations of changing physical/psychological and/or thermal stress. A further main task will be the development of well-suited set-ups of the MiCS for special applications, where besides ventilation and cooling also heating of the ventilated air and/or dehumidification are system options. The advanced MiCS will have special inlet and outlet connecting elements which can readily be attached to, detached from and exchanged for one another on the gas flow channels for supplying and discharging gas streams that are to be heated or cooled. The MiCS of the future will also have a significant lower total mass with the usage of thinner metal sheets for both the evaporator and the adsorber unit.

Future application fields for the innovative MiCS are in the civil domain, e. g.:

- gas-tight chemical protection suits for chemical spillage fighters
- racing suits
- dry diving suits
- closed-circuit breathing devices
- heat protection suits for fire fighters
- special emergency equipment (casualty litter bags)

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An Enhanced Personal Cooling Garment for Aircrew

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SUMMARY

A novel enhanced personal cooling garment (EC) for aircrew was tested on seven male subjects who were clad in full immersion protective aircrew clothing and exposed to 40C and 20% relative humidity for three hours. For comparative purposes, the subjects also wore current air-cooling vest (AC) alone. Two test protocols were used. One protocol provided the subjects with personal cooling throughout the three-hour trial; the other protocol did not allow the subjects to use their personal cooling for the first hour of the three-hour trial. The enhanced personal cooling garment prototype was shown to enhance the level of cooling provided by existing air-cooled vests, thus providing potential physiological benefits and hence greater comfort to aircrew.

INTRODUCTION

Aircrew conducting flight operations in hot environments are susceptible to heat stress. Heat stress can invoke physiological and psychological responses that are dangerous to aircrew performance and hence safety [1,2].

Current approaches to aircrew cooling involve either liquid (LC) or air cooled (AC) garments. LC vests are worn by helicopter crews and astronauts. A typical system is comprised of a two-liter block of ice acting as a heat sink, and a garment fitted with a network of tubing through which chilled water is circulated by a small DC-powered pump. Cooling is due primarily to conductive heat transfer from the skin and clothing microenvironment to the water, across the tubing wall. While such systems are portable and robust, they are heavy (≈ 4 kg) and require frozen water and electrical power. They offer limited heat extraction; good performance requires tubing to remain in contact with the body.

AC vests distribute low-pressure air over the aircrew member’s torso. AC vests are worn in aircraft offering conditioned airflow. Typically, AC vests consist of a spacer material sandwiched between perforated air impermeable fabrics through which climate controlled air is passed. AC systems generally provide higher amounts of cooling and keep the wearer drier than LC systems.

Mustang Survival Corporation recently developed a prototype Enhanced Personal Cooling Garment (EC) which uses a different approach than existing AC or LC [3,4]. The EC vest is constructed and worn in a manner that positions a thin layer of water next to the wearer’s skin. The vest is constructed of highly vapour permeable, yet liquid impermeable fabrics. When filled with water, it remains thin (<2mm) to minimize the inherent insulation of the EC garment itself. Preliminary testing by Mustang Survival showed cooling is achieved as water diffusing from the vest extracts its heat of vaporization from the fabric layers. The EC vest is lightweight (0.4 kg empty and 0.9 kg filled) with no moving parts.

Paper presented at the RTO HFM Symposium on “Blowing Hot and Cold: Protecting Against Climatic Extremes”, held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

Tests on a guarded sweating hot plate indicated that when EC was worn below AC, the combination was capable of providing higher heat loss than AC alone. Tests also showed moisture introduced beneath EC will also diffuse through the vest. Based on these preliminary findings, full human subject testing was considered as necessary to further quantify and validate the vest's potential as an enhanced personal cooling garment for aircrew. This paper details the methods and results from human subject tests [5].

METHODS

Subjects

Seven healthy, non heat-acclimated male volunteers comprised two test groups. Three of the subjects (group N) experienced greater heat stress by depriving them of cooling for the first hour of the test. Four of the subjects (group C) were provided with cooling throughout the duration of three-hour trial.

Mean values (±SD) for age, weight, height, and chest circumference for group N subjects were 22.7±1.7 yrs, 74.3±10.7 kg, 171.5±1.7 cm and 96.4±8.3 cm, respectively. Mean values (±SD) for age, weight, height, and chest circumference for group C subjects were 26.8±3.7 yrs, 79.7±14.6 kg, 178.6±8.5 cm and 99.8±7.4 cm, respectively. All subjects were provided with an information sheet outlining experimental details and risks and signed an informed consent form prior to commencing any tests. Additionally, all subjects were instructed not to consume caffeine for 12 hours prior to testing and alcohol for 24 hours prior to testing.

Experimental Protocol

All subjects participated in two test sessions, one trial with air cooling alone (AC) and another with both air and enhanced cooling (EC) separated by a minimum of two days (in random order). Each subject wore briefs, cotton-polyester long underwear, wool socks, leather flight boots, aviation immersion coveralls (Mustang MAC 200), flight gloves, life preserver and survival vest (Mustang MSV971), flight helmet, anti-G trousers (CSU-13 B/P), AC vest (Mustang MSF833) either with or without the prototype EC vest. Each subject was seated in an ejection seat within an environmental chamber at 40.1±0.1°C and 19.8±1.8% RH with a fan providing a wind speed less than 0.1 $m \cdot s^{-1}$. All subjects were provided with 1 litre of water to drink over the course of the experiment (if necessary) and allowed to view a movie of their choice. Test termination criteria was set as either reaching a duration of 3 hrs, the subject's rectal temperature exceeding 39°C (or 2°C above initial temperature), the subject exhibiting symptoms of dizziness, nausea, or weakness, the subject asking to withdraw, or the experimenter deciding to terminate the experiment.

Description of Cooling Systems

The AC vest was a Mustang Survival MSF833. The bladder of the AC vest is made from two layers of impermeable polyurethane-coated nylon separated by a spacer material that acts as an air distribution manifold. The innermost layer of the polyurethane-coated nylon is perforated to direct escaping air towards the wearer's body. A second layer of spacer material between the perforated fabric and body ensures air distribution over the torso. The vest exterior is covered with aramid cloth. Cool air for AC was provided by blowing air through a heat exchanger immersed in an ice bath maintained at 2-5°C. This yielded a flow rate of 393.6±8.5 $L \cdot min^{-1}$ (13.9±0.3 SCFM) at a vest inlet temperature of 23.2±0.5°C.

The EC garment was a front-zippered vest made of vapour permeable, polyurethane-coated stretch nylon, radio frequency welded to produce a network of channels through which water could migrate under capillary action. Water entered the vest through an inlet valve at the waist and trapped air was vented from three PTFE patches located at shoulder level. The EC was connected to a water reservoir suspended 1.4 m (4.6 ft) above the vest inlet to produce a maximum hydrostatic pressure of approximately 14 kPa (2 psi). Once connected to the reservoir, EC was self-filling, drawing water from the reservoir only as it evaporated from

the vest. Water consumption was measured by periodically recording the reservoir water level. The vest was fit snug by adjusting speed lacing along the shoulders and edges of the front zipper.

Dressing and Weighing Procedures

Subject preparation involved subjects instrumenting themselves with a rectal thermistor (inserted 15 cm) and weighing themselves to determine pre-trial nude weights (with thermistor), while their briefs were weighed separately in a plastic bag. Wearing shorts, the subjects were instrumented with heart rate electrodes, temperature thermistors at six sites and heat flux transducers at five sites. All articles of clothing were individually weighed in plastic bags and handed to the subject for immediate donning. Prior to the subject entering the environmental chamber, a bottle of water was weighed and given to the subject for consumption during the test (if desired).

Immediately following termination of the experiment (within 10 minutes) each article of clothing was again individually weighed in a plastic bag and the subject’s nude weight recorded prior to removal of the rectal thermistor. Additionally, the subject’s water bottle was weighed to determine the amount of water consumed during the trial for later correction of the subject’s post-trial nude weight. Sweat production was calculated as the difference between corrected pre-trial and post-trial subject nude weights.

Data Acquisition

Data from all temperature thermistors (YSI 400) and heat flux transducers (Concept Engineering) along with the cooling vest air inlet temperature, environmental chamber temperature and relative humidity were recorded every minute by a remote data logger (Grant 1250 series Squirrel meter/logger). Values for all of the above as well as core temperature, cooling air flow rate, and heart rate were recorded manually at ten minute intervals.

Ratings of Thermal Comfort

Thermal comfort was rated by the subject on a scale of 1 (so cold I am helpless) to 13 (so hot I am sick and nauseous) at ten minute intervals.

Statistical Analyses

All data are presented as mean values and the standard deviation of the mean. Mean skin temperature and heat flux is weighted by skin surface area. A one-tailed paired T-test (95% confidence level) was used to compare C-AC to C-EC and N-AC to N-EC. ANOVA and Tukey-Kramer post-hoc analysis was used for comparison between groups.

RESULTS

Heart Rate

Figure 1 shows the average heart rate of group C and N. During the final two hours of the test, mean heart rate of group N was very significantly lower wearing EC than AC ($p<0.005$). The mean heart rate of group C was also significantly lower wearing EC than AC ($p<0.0001$). Note that during the final hour of testing, mean heart rate of group N-EC was comparable to that of C-AC and C-EC.

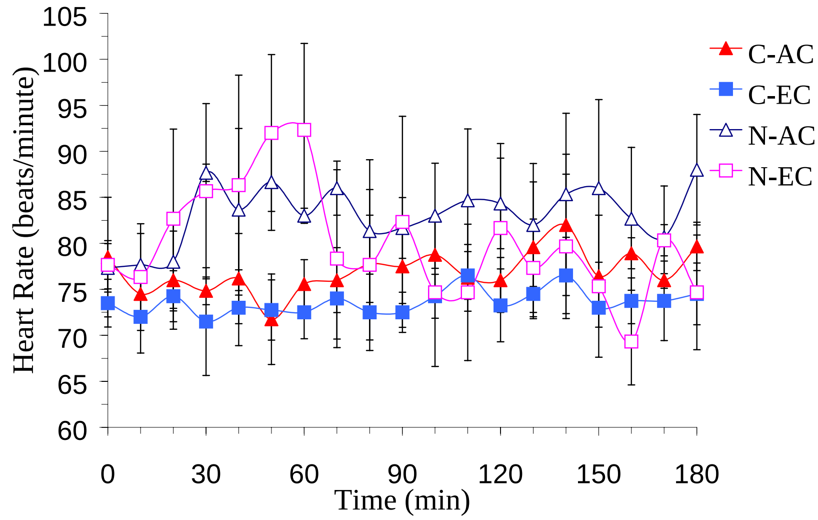

Figure 1 – Heart Rate

Rectal Temperature

Figure 2 shows the mean change in rectal temperature of group C and N.

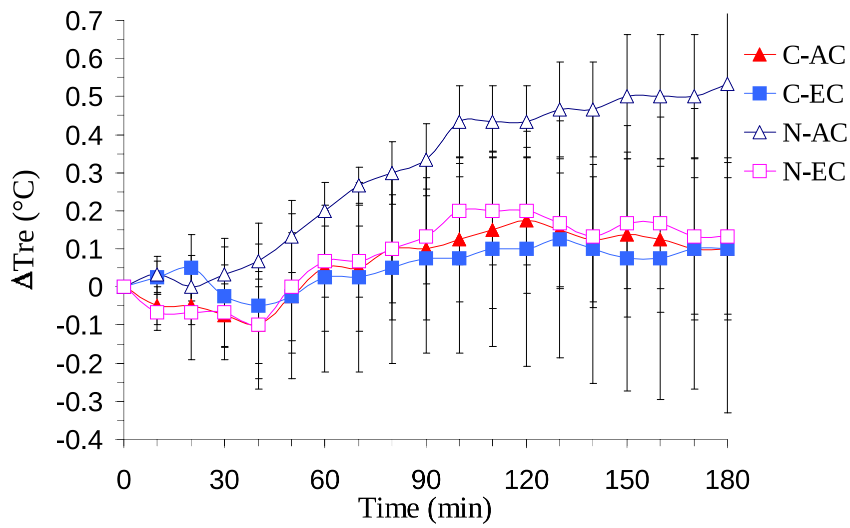

Figure 2 – Change in Rectal Temperature

The greatest increase in mean rectal temperature was observed with group N wearing AC. The mean change in core temperature of group N was significantly lower while wearing EC than AC ($p<0.0001$). For group C, mean change in core temperature was not significantly different between AC and EC ($p>0.05$). It is of interest to note that mean change in core temperature of group N-EC (whose protocol subjected them to greater heat stress) not significantly different from group C ($p>0.05$).

Mean Skin Temperature of Cooled Sites

Figure 3 shows the mean skin temperature of the cooled sites for group C and N. These two sites were the abdomen and mid-back. The highest mean skin temperature of the cooled sites was observed for group N during the first hour in which no cooling was provided. With both group C and N, the mean skin temperature of the cooled sites was significantly lower wearing EC than AC ($p<0.0001$). Note that within 20 minutes of activating EC, group N exhibited mean skin temperatures of the cooled sites comparable to those of group C-AC. After one hour of activating EC, mean skin temperatures of the cooled sites of group N-EC were comparable to those of group C-EC. Once cooling is activated, both groups using EC had lower skin temperatures than AC.

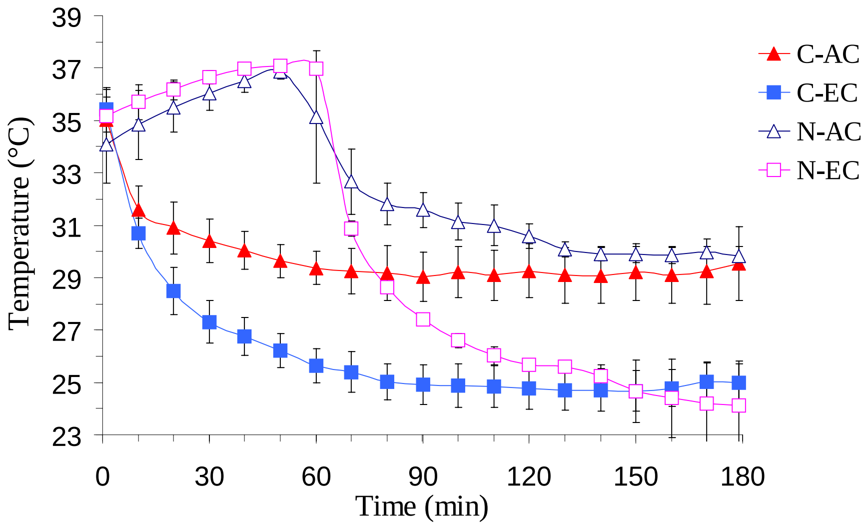

Figure 3 - Mean Skin Temp (cooled sites)

Mean Skin Temperature of Uncooled Sites

Figure 4 shows the mean skin temperature of the uncooled sites for group C and N. The four sites were the calf, thigh, bicep and forearm.

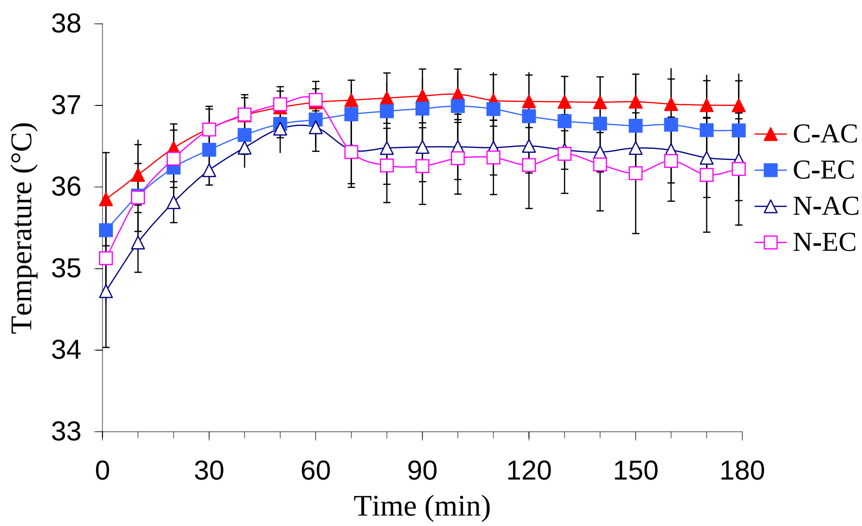

Figure 4 - Mean Skin Temp (uncooled sites)

The mean skin temperature of the uncooled sites of group N was significantly lower with EC than AC ($p<0.01$). With group C, the mean skin temperature of the uncooled sites was significantly lower with EC than AC ($p<0.0001$).

Mean Heat Flow of Cooled Sites

Figure 5 shows the mean heat flow of the cooled sites for group C and N. These two sites were the abdomen and mid-back.

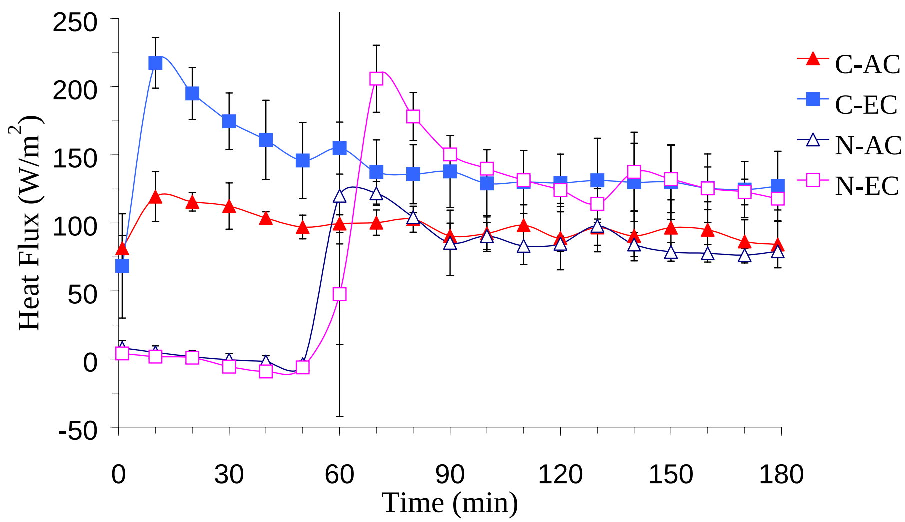

Figure 5 - Mean Heat Flow (cooled sites)

During the first hour, group C had higher mean heat loss from the cooled sites than group N. During the first hour, group N had essentially no heat loss from cooled sites rather these sites exhibited heat gain. This was as expected as cooling was not activated during the first hour for group N. Group C had significantly greater mean heat loss from cooled sites while wearing EC than AC ($p<0.0001$). During the last two hours, group N had significantly greater mean heat loss from cooled sites while wearing EC than AC ($p<0.001$). .

Upon activation of cooling, mean heat loss from the sites beneath EC was greater than beneath AC, regardless of group. Mean heat loss from cooled sites of EC was approximately 50 $W \cdot m^{-2}$ (or 50%) greater than AC.

Mean Heat Flow of Uncooled Sites

Figure 6 shows mean heat flow of the uncooled sites for group C and N. These three sites were the thigh, bicep and forearm. During the first hour, mean heat flow from the uncooled sites was not significantly different between groups. For group C, mean heat flow from the uncooled sites was significantly higher with EC than AC ($p<0.0001$). For group N, mean heat flow from the uncooled sites was significantly higher with AC than EC ($p<0.0001$).

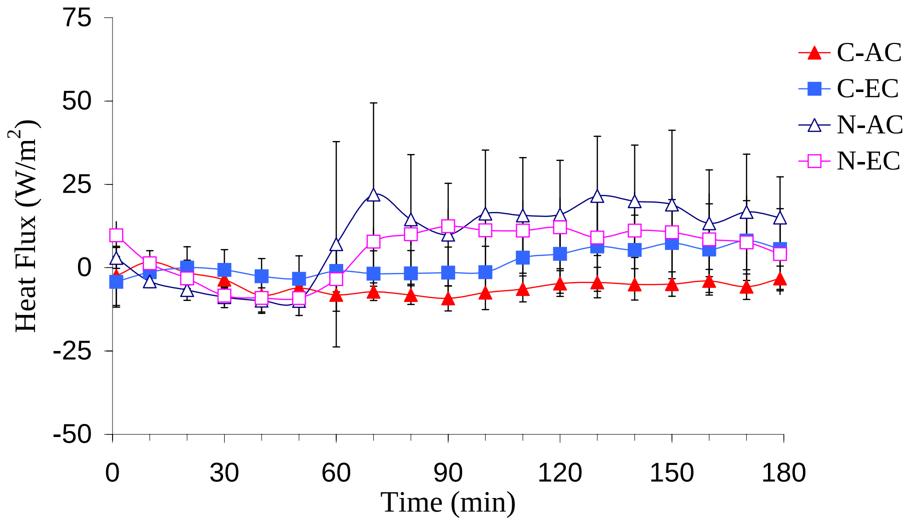

Figure 6 - Mean Heat Flow (uncooled sites)

Rating of Thermal Comfort

Ratings of thermal comfort for group C and N are shown in Figure 7.

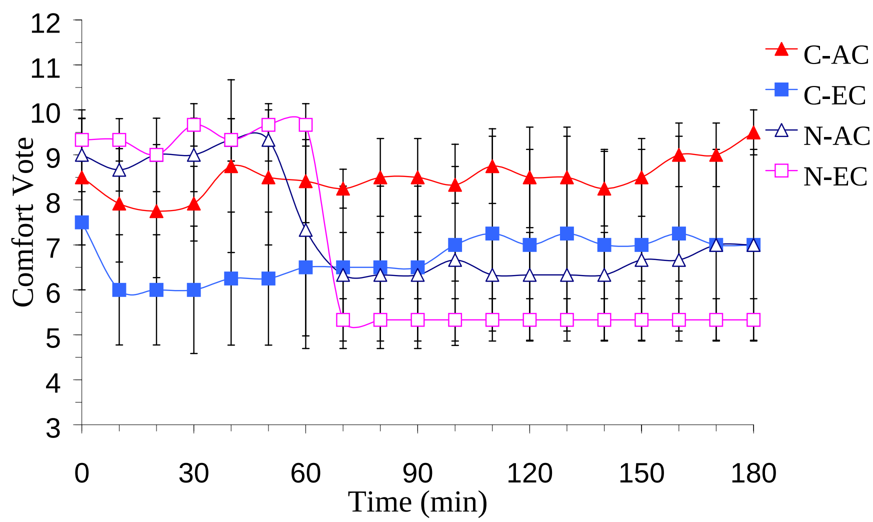

Figure 7 - Rating of Thermal Comfort

During the first hour, group N rated themselves as warmer than group C. This is consistent with expected differences due to protocol. With EC, group C and N felt significantly cooler ($p<0.0001$ and $p<0.005$, respectively) than with AC.

Hydration Status

Changes in nude body weight for group C and N are shown in Table 1.

Table 1 – Body and clothing weight change

Group-Vest	*Body Weight Loss (g)*	*Clothing Weight Change (g)*
C-AC	600.8 ± 315.0	-80.6 ± 79.9
C-EC	362.9 ± 184.0	-4.3 ± 53.0
N-AC	566.8 ± 34.4	26.6 ± 88.8
N-EC	604.8 ± 226.0	107.8 ± 63.8

There were minimal differences between body weight loss with C-AC, N-AC and N-EC. Group C wearing EC lost considerably less weight due to sweating and respiration than the others. It is possible that lower skin temperatures reduced the sweating response.

With Group C, clothing weights were less after completion of testing than before. With Group N, the clothing weights increased for both AC and EC. This is likely due to greater sweating induced by the one-hour heat stress of Group N. Within a given group clothing remained drier with AC than EC. This is probably due EC introducing moisture to the clothing microenvironment.

DISCUSSION

The findings from the present study show the effectiveness of both air-cooling and a prototype air-liquid cooling system when worn beneath full military aircrew clothing ensembles. The enhanced cooling system (EC) provided a greater cooling capability than air-cooling alone. Use of EC resulted in reduced heart rates, lower rectal and skin temperatures, greater heat loss from the body and improved thermal comfort than with use of AC alone.

The current prototype EC system is lightweight and can easily integrate into existent aircrew clothing ensembles. The logistics of providing water to the vest require further consideration. Currently, the vest can be filled and detached from its reservoir, although this would limit its operational duration. When left connected to a low-pressure reservoir the vest is capable of self-replenishing hence its operational duration would depend on reservoir volume. Hot plate testing and preliminary human testing indicates the EC vest provides cooling without the presence of AC. Its cooling capacity is dependent on the water vapour pressure gradient between the plate and ambient environment. The magnitude of passive cooling has been quantified on a sweating hot plate but not on human subjects. This capability may offer cooling outside the cockpit environment during transit to and from aircraft as well as post-ejection.

The durability and hence leak-tightness of the vest during maneuvers which induce high G-load in the cockpit requires investigation. While the vest is still at an early prototype stage, its performance is promising and warrants further investigation.

CONCLUSION

Based on limited human subject testing, it is concluded that the prototype Enhanced Personal Cooling Garment (EC) provided significantly lower mean core and skin temperatures than AC alone. Heart rate was significant lower with subjects wearing EC than AC and test subjects rated themselves as significantly cooler while wearing EC than AC. This was due to significantly greater heat loss from the torso wearing EC than AC. The EC prototype was found to enhance the level of cooling provided by a typical aircrew AC vest.

ACKNOWLEDGEMENTS

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Cooling Individuals Using Encapsulating Protective Clothing in a Hot Humid Environment

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ABSTRACT

Introduction: Persons responsible for removing extremely hazardous chemical agents or responding to chemical incidents typically wear fully encapsulating chemical protective ensembles (Level A) during field operations. Level A ensembles are currently used without any ancillary cooling system thereby greatly increasing the risk of thermal injury. The present study evaluated 4 candidate cooling systems intended to mitigate thermal stress experienced by Level A ensemble users in hot humid conditions. **Methods:** Four current members (males, ages = 22-24) of a military chemical response unit served as subjects in this study. Participants wore operationally configured Level A ensembles with a closed circuit soda-lime based re-breather system while performing repeated rest (5 minutes)/work cycles (25 minutes: alternating treadmill walking (4.8 km hr^{-1}, 5% grade) and level walking while carrying 22.7 kg) designed to simulate tasks and workloads associated with actual missions for up to 2 hours. Air temperature was maintained at 37°C with relative humidity = 75% throughout exposures. Tested cooling systems were: 1) liquid cooled vest with hood (ice cooling source); 2) phase change vest; 3) wetted vest; and 4) liquid cooled whole body garment (super critical air cooling source). The non-cooled Level A configuration served as the experimental control. **Results**: No significant differences were observed between control and cooling runs. Subjects were unable to complete more than 2 rest work cycles (mean ± S.D. = 47.9 ± 8.5 minutes) while experiencing changes in rectal temperature = 1.4 ± .4 °C and maximum heart rates = 167 ± 11beats min^{-1}. Runs terminated either because of breathing difficulties, high heart rates, or subject exhaustion. **Conclusions**: None of the cooling systems proved effective in overcoming the severe heat stress imposed on subjects. Hot breathing gas coming off the re-breather was originally thought to be a major factor contributing to the thermal burden but this proved incorrect. Conventional cooling methods appear entirely inadequate to address the combined stressors of high ambient temperature and humidity coupled with demanding physical workload.

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

BACKGROUND

Impermeable or semi-permeable garments providing protection against chemical and biological warfare agent (CBW) threats can retain large quantities of body heat. Body heat trapped within these encapsulating garments needs to be removed if the garment user is to adequately perform required tasks, especially when users are physically active. Otherwise, trapped heat leads to hyperthermia, a potentially dangerous condition that can severely degrade mission performance, cause injury, and in extreme cases, result in death.

The U.S. Marine Corps (USMC) Chemical Biological Incident Response Force (CBIRF) routinely employs encapsulating CBW protective garments in all environmental conditions while performing a variety of demanding physical tasks. CBIRF personnel experience performance degradation and reduced endurance while wearing these garments during training and actual missions. They are currently investigating a number of advanced cooling concepts that can theoretically address this problem. The present study was intended to evaluate four advanced cooling methodologies (hydro-weave suit (HW), liquid cooled vest (LCV), phase change vest (PCV), and Super Critical Air Mobility Pack (SCAMP)) in combination with compatible chemical protective outer garments (CPOGs) ensembles.

METHODS

The purpose of this study was to identify cooling systems which maximize an individual's tolerance time in hot/humid environments by mitigating heat related degradation of physical endurance and strength experienced while wearing a fully encapsulating CBIRF CPOG during simulated operational tasks.

<u>Subjects</u>: The experimental protocol was approved by the Naval Air Warfare Center Aircraft Division (NAWCAD) Institutional Review Board in accordance with Department of Defense and U.S. Navy requirements. Four healthy male Marines currently assigned to CBIRF volunteered to particpate after being fully informed of the details of the experiment protocol and associated risks. These four subjects routinely perform rigourous physical tasks in CPOGs under a wide variety of environmental conditions. Consequently, study conditions were judged to reflect conditions these individuals would experience during normal operations (i.e., training or actual operations). Table 1 lists the physical characterisitics of the subjects. Body surface area was calculated from the height and weight of each subject (5) and % body fat was calculated from skinfod measurements (6, 19).

Table 1. Physical characteristics of subjects.

Subject	Age	Height (cm)	Weight (kg)	Surface Area (m^2)	% Body Fat
A	23	168	72.8	1.82	16.7
B	23	188	83.4	2.10	13.9
C	22	180	80.6	2.00	17.0
D	24	175	81.9	1.98	11.9
Mean ± std. dev.	23 ± .8	1.78 ± .08	79.7 ± 4.7	1.98 ± .12	14.9 ± 2.4

<u>Cooling Systems (Table 2)</u>: Five distinct cooling systems were employed in this study. Two of these systems also provided breathing air (SCAMP, APACS) while the others (HW, LCV, PCV) relied upon an external breathing source in this study.

Liquid cooled ***vest (LCV)***: Two systems (LCV, SCAMP) employed liquid-filled tube garments to extract heat from the body surface. The LCV tube garment consisted of a water-filled tubed shirt and hood worn directly over the skin. Conduction (and some convection) transferred heat from the skin to the circulating fluid. Water passed from the tubing through an ice filled bottle and then recirculated through the tubing via a pump directly attached to the ice bottle. A tubing pass-through enabled cooled water to enter and exit the tubing garment without compromising LA garment integrity. Mounting the LCV cooling unit onto LA was accomplished by a hook mounted onto a reinforced point on the LA surface. A strap system mounted opposite the supporting hook was intended to transfer the ice bottle/pump weight onto the weight bearing straps from the breathing system.

Table 2. Cooling systems evaluated in present study.

Item	Study Notation	System Weight (kg)	Cooling Technology	Primary Heat Transfer Mechanism
1	LCV	6.0	Liquid cooled tube suit (water/ice)	Conduction
2	PCV	2.9	Phase change beads (hydrocarbon wax)	Conduction
3	HW	1.4	Water-soaked vest	Evaporation
4	SCAMP		Liquid cooled tube suit Cooled breathing gas	Conduction Respiratory evaporation

Phase change vest (PCV): An open-weave mesh vest containing hundreds of small plastic coated wax beads comprised the PCV. Convection extracted heat from the skin and melted the wax. PCV vests were worn over a tee shirt to prevent chaffing and covered both the entire torso and upper shoulders.The open weave mesh permitted air flow through the vest during use.

*Hydroweave vest (****HW****)*: The HW was prepared by soaking the lightweight porous fabric vest containing a hydrophilic inner lining in water and wringing it out. Cooling occurred when heat released from the skin evaporated the trapped water. The vest was worn over a tee shirt to prevent chaffing and covered most of the torso.

Table 3. Components of the test clothing ensembles.

ENSEMBLE	SYMBOL	System Wt. (kg)	COMPONENTS
CBIRF Level A CPOG	LA	22.3	• Fully encapsulating Tyvek outer garment with plastic face shield and integral booties • Litpac II soda-lime rebreather (LA-L) -or- Compressed air self-contained breathing apparatus (LA-S) • Cotton blend shirt & trousers, underwear, socks • Chemical-resistant boots

Supercritical air cooling package (SCAMP): A full coverage (arms, legs, torso) tubing suit worn next to the skin was used to extract heat from the skin. Polyethylene glycol passing through the tubing transferred heat to a heat exchanger through which supercritical air (-193°C) passed as part of the breathing loop. The supercritical air removed heat from the circulating propylene glycol and was consequently warmed to an acceptable breathing temperature. A Dewar bottle chilled with liquid nitrogen retained the supercritical air under low pressure (750 psi) for both body cooling and as breathing gas.

CPOG (Table 3): ***Level A (LA)***: A single-piece, impermeable, and totally encapsulating garment completely seals the user from the external environment. A supplemental breathing source worn inside the LA supplies oxygen to the user. LA was used with either a soda-lime based LITPAC rebreather (approx. fully charged wt. = 18.2 kg) (LA-L) or self-contained breathing apparatus (approx. fully charged wt. = 17.3 kg) (LA-S) in this study.

Experimental Design: The study was designed to expose each test subject to five experimental trials (Table 4). The study intended to identify the most effective of four cooling systems (HW, LCV, PCV, SCAMP) by measuring work endurance in a hot/humid environment while wearing LA. The current operational configuration (LA-L with no supplemental cooling) was used as the experimental control. Short exposure durations in the earlier runs led to adding additional runs to assess the effect of breathing system (self-contained rebreather (LITPAC) vs. pressurized air bottles (SCBA)) on exposure tolerance.

Experimental Conditions: Environmental conditions were selected to reflect some of the more extreme environments CBIRF personnel are exposed to during training and operations. Air temperature (T_{air}) = 37°C and relative humidity (RH)=75% were chosen to reflect hot summer days in Southeastern United States or the Persian Gulf. Workloads were imposed to reflect the physical tasks performed by CBIRF personnel in the field. CBIRF personnel perform many of their field tasks while wearing CPOGs including walking from vehicles to a contaminated site, carrying equipment into and about the site, and dragging injured individuals from the site. To simulate these activities, subjects attempted to complete 4 consecutive rest/work cycles comprised of five minutes of rest (R period) followed by 25 minutes of light to moderate work (Figure 1). These work periods were comprised of three 5 minute bouts of treadmill walking (4 – 5.6 km hr^{-1} (2.5 to 3.5 mph) at 5% grade) (T period) interspersed with two 5 minute periods of carrying weights (two 11.3 kg (25 lbs) barbells) repeatedly across the chamber (W period). Subjects carried weights across the chamber only on alternating walks during W periods because of excessive strain on their hands and forearms. Brisk walking to and fro across the chamber (a total distance of approx. 15 m) replaced treadmill exercise in 8 of 23 runs because of treadmill failure.

Table 4. Experimental design to assess cooling techniques

Condition #	CPOG	Cooling Systems
1	LA-L	PCV
2	LA-L	HW
3	LA-L	LCS
4	LA-L	SCAMP
5*	LA-L	none

* - experimental control, current USMC CBIRF configuration

Instrumentation: Two temperature probes (model 4491E, Yellow Spring Instr., Yellow Springs, OH) inserted 10 cm anterior to the anal sphincter measured rectal temperatures (T_{re}) during exposures. Four skin surface temperature probes (model 4499E, Yellow Spring Instr., Yellow Springs, OH) measured upper left chest (T_{chest}), upper right arm (T_{arm}), anterior thigh (T_{thigh}), and lateral shin (T_{shin}) temperatures. Temperature probes were interfaced with VitalSense temperature telemetry systems (Mini Mitter Co., Sunriver, OR). In addition, inlet and outlet airstream temperatures and air temperatures just behind the visor were measured within the LITPAC and SCBA masks with 36 AWG (.05 mm dia.) type T thermocouples. Thermocouple signals were collected and processed with a thermocouple data logger (model SmartReader Plus 6, ACR Systems, Surrey, BC, Canada). The temperature measurement system was calibrated at 2 points with a constant temperature (29.7718°C) Gallium cell (model 17402, Yellow Springs Instruments, Yellow Springs, OH) and a zero-point (0°C) cell (model K140-4, Kaye Instruments, Bedford, MA). Heart rate was displayed on an ECG monitor (model Visa II, Datascope, Inc., Paramus, NJ) and recorded with a heart rate monitor (model Xtrainer Plus, Polar Electro, Kempele, Finland). Clothed and nude body weights were measured with an electronic scale accurate to ± 50 g (model FV-150K, A&D Ltd., Tokyo, Japan).

Subjects were asked to subjectively rate their comfort, sweating, and fatigue, and temperature (comfort scores) on a seven point scale every 15 minutes. Comfort, sweating, and fatigue were reported using a scale of increasing distress (e.g., for fatigue: 1 = very rested, to 7 = extremely exhausted) and temperature was reported as 1 = very cold, 4 = neutral, to 7 = very hot.

Experimental exposures: Each subject generally reported to the laboratory at roughly the same time (early (7-9 AM) or late (10–12 AM) morning) each day they participated. A brief physical exam and medical history was conducted when subjects entered the laboratory dressing area to begin each trial. Mean ambient air temperatures maintained inside this preparation area = 22.5° ± .2°C. Initial comfort scores were obtained prior to obtaining semi-nude weight (with underwear and rectal probes) ($m_{i,nude}$) after subjects inserted their rectal probes. Four ECG electrodes attached to the upper torso were adjusted to obtain the clearest signal and skin thermocouples were taped to the subject (Transpore tape, 3-M, Minneapolis, MN). A Polar heart rate transmitter was placed on the chest after moistening the contact surface with water. The subject was then dressed in the remaining clothing items and the cooling and breathing systems mounted on the subject. Telemetry transmitters (i.e., VitalSense (temperature), Datascope (ECG)) were affixed to the breathing apparatus (LITPAC, SCBA, SCAMP). The ACR datalogger for collecting respiratory mask temperatures was mounted on the top of the LA breathing apparatus at this time. The Polar wrist receiver was affixed to a chest strap just prior to sealing the CPOG. Computer data collection began roughly after the skin temperature probes were affixed to the skin but useful data collection (i.e., stable reliable data) generally began at approximately the t = -5 minute mark. Clothed weight ($m_{i,clothed}$) was obtained immediately after garments were sealed and then subjects entered the chamber to begin experimental exposures.

Subjects entered the environmental chamber at t = 0 and began a series of up to four consecutive rest/work cycles. Chamber conditions for all runs were fixed at T_{air} = 37.0 ± 0.2°C and RH = 75 ± .7%. Subjects seated at a small table completed questionnaires and provided comfort scores (estimated metabolic rate =195 W assuming metabolic output for writing (11) given a mean clothed weight = 99.6 ± 8.2 kg) during the initial R period. At the end of five minutes, subjects began the first T period (estimated metabolic rate = 637 (13) -710 W (22)). Subjects were instructed to walk briskly across the chamber on those occasions when a treadmill was malfunctioning (estimated metabolic rate = 562-683 W at 4 mph (13, 22)). This represented a 4% decrease in workload with walking versus treadmill. Two alternating W (estimated metabolic rate = 746 W (3)) and T periods completed the first rest/work cycle. These rest/work patterns produced an mean estimated time-weighted metabolic rate of 572-636 W (assuming treadmill use) and represent a heavy (12) or continuous (13) workload while bearing 20 kg. Estimated metabolic rates for lighter garments (10kg) were approximately 10% less (11). The third R period was designated the time for replacing breathing apparatus or bottles. In practice, however, breathing system replacements often occurred prior to the third R period due to unanticipated high breathing rates. Ice bottles (LCV runs) were replaced when requested. Subjects were not provided water or food during exposures because drinking or eating are not provided for in the LA design and would require removing the CPOG. This is consistant with field conditions; drinking occurs prior to doning a LA CPOG or subsequent to its removal but not while wearing it.

Chamber exposures terminated when (a) subjects completed 4 rest/work cycles, (b) they requested removal, (c) T_{re} increased to 39°C**,** (d) a subject's sustained heart rate (HR) reached 90% of estimated maximum safe heart rate for age (220 - age in years), or e) critical equipment failure occurred. Clothed weight ($m_{f,clothed}$) was obtained immediately upon exiting the chamber**.** Subjects were then seated and rested for approximately 15 minutes while their T_{re} was monitored. Subjects were released to remove their rectal probes and take a shower once T_{re} dropped below 38°C. Final semi-nude weight ($m_{f, nude}$) was measured after the shower and then subjects were medically cleared to leave the laboratory.

Physiological Indicies: Physiological temperatures were analyzed as differences (e.g., $\Delta T_{re} = T_{re,\,final} - T_{re,\,initial}$) over an exposure period because within-subject initial temperatures varied between exposures. Mean weighted skin temperatures were calculated using the method of Ramanathan (15):

[1] $$T_{sk} = 0.3(T_{chest} + T_{arm}) + 0.2(T_{thigh} + T_{shin})$$

Total sweat losses, SWL, including evaporation and dripping, was

[2] $$SWL = m_{i,\,nude} - m_{f,\,nude} + \text{water consumed}$$

and the amount of sweat absorbed by the clothing was calculated by

[3] $$\Delta GW = (m_{f,clothed} - m_{f,\,nude}) - (m_{i,clothed} - m_{i,\,nude}).$$

Figure 1. Planned rest and work periods for an individual trial. Each rest or exercise period (R, W, or T) had a 5 minute duration and total exposure times were intended to last up to 240 minutes. Subjects entered the environmental chamber at the start of rest period #1. Exchanging depleted breathing systems was intended to occur during rest period #3. R = rest periods, T = treadmill (or brisk walking), W = walking with two 25 kg weights across the chamber

	Work Cycle						Work Cycle						Work Cycle						Work Cycle				
R	T	W	T	W	T	R	T	W	T	W	T	R	T	W	T	W	T	R	T	W	T	W	T
Duration of rest/work cycles (minutes)																							
5	25					5	25					5	25					5	25				

Data Analysis:

The central hypothesis of this study was that at least one cooling system would generally enable users to tolerate exposures of greater than 60 minutes. Exposure tolerance was broadly defined as retaining the volition or physical ability to continue performing physical and mental tasks while exposed to experimental conditions. Independent variables were defined as the protective ensemble and cooling system. Dependent variables were rectal temperature (T_{re}), skin temperatures, heart rate (HR), sweat loss, salivary amylase concentration, and subjective stress assessments.

A sample size of 4 was chosen as a compromise between statistical power and study cost and duration. This sample size provides a statistical power, $1-\beta$, of 0.873 when using an analysis of variance to compare mean final T_{core} between 4 individuals exposed four times (once per clothing configuration) assuming the study detects T_{core} differences = 0.3°C with a standard deviation = 0.1°C. Reducing the sample size to 3 subjects drops the statistical power of the paired-t test to $1-\beta = 0.745$. The intent was to have a balanced experimental design for subsequent statistical analysis.

Nearly all experimental conditions had an n = 4; subject illness limited LA-L/HW runs to an n=3. Final values were tested for between-subject variability with a non-parametric Kruskal-Wallis analysis of variance (ANOVA). One goal in analyzing study data was to use each subject as their own control and eliminate between-subject variability. A non-parametric Friedman ANOVA was employed to analyze within-subject variability. When the ANOVA detected significant differences among configurations, a Newman-Keuls post hoc test was used to identify those configurations which differed significantly from the others. Linear correlation analysis was used to assess relationships between variables. Data are reported as mean value ± standard deviation. Differences were considered significant at the $\alpha = .05$ level.

RESULTS

In general, study conditions did not identify any of the tested cooling systems as significantly more effective in mitigating the thermal stresses imposed by environmental conditions and physical workloads. Physical and mental tolerance, measured by exposure duration, and physiological responses to the thermal stresses were statistically indistinguishable by most measures with three factors causing the majority of run terminations: HR, fatigue, and breathing difficulties. In general, however, cooling systems did not significantly affect exposure durations (Figure 2) as observed in both between- and within-subject analyses.

Though breathing gas temperatures in LA-L runs were deemed hot and many runs terminated for subjective intolerance to breathing hot air, any breathing system effects were not determined to be statistically significant. Initially, subjects subjectively attributed short LA-L exposures to breathing heated air generated by the LITPAC rebreather. Soda lime contained in the LITPAC removes CO2 from the exhaled airstream but the chemical reaction generates heat. This increases LITPAC temperature and the inhalation gases coming out of the unit. In contrast, SCBA consists of compressed air bottles; expanding breathing gas cools as it exits the bottles. There are no exothermic chemical reactions to generate heat in the SCBA breathing system. Comparison between LITPAC and SCBA mask inlet temperatures, however, indicated that breathing gas temperature was independent of breathing system while wearing a LA. Strong correlation of inlet mask temperature with ambient temperature (Figure 3, $r^2 = 0.91$ (LITPAC), $r^2 = 0.81$ (SCBA)) demonstrated that mask inlet temperature was primarily a function of the interior LA air temperature. In addition, no significant differences in exposure duration, ΔT_{re}, total sweat loss, or sweat rate between LITPAC and SCBA runs were observed. Consequently, use of either the LITPAC or SCBA did not significantly affect exposure durations due to breathing gas temperature.

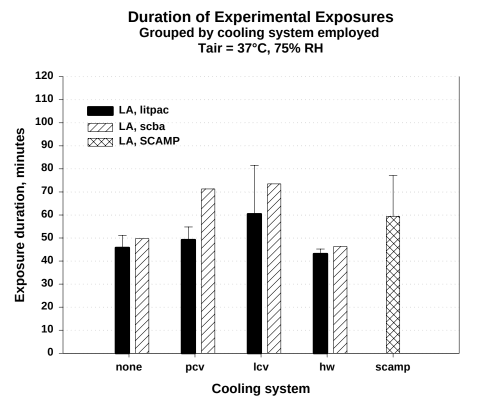

Figure 2. Exposure durations observed as a function of cooling system.

PHYSIOLOGY: A strong positive linear correlation existed between exercise duration and T_{re} ($r = .795$; $p < .001$). Overall, between-subject analysis demonstrated no significant ΔT_{re} differences between configurations (Figure 4). Within-subject analysis, however, showed cooling systems effects were inconsistent with different systems producing the smallest ΔT_{re} depending on the subject. LA-L/LCV produced the smallest ΔT_{re} in subjects A (along with LA-L/PCV) and B. LA/SCAMP produced the smallest ΔT_{re} in subject C while LA-L/control and LA-S/HW generated the smallest ΔT_{re} in subject D.

Maximum HR did not vary significantly between configurations in between- or within-subject comparison. HR variation over the course of an exposure also did not differ significantly (Figure 5). Not surprisingly, T_{re} correlated to heart rate ($r = .495$; $p = .003$).

Sweat losses did not vary significantly between CPOG/cooling system configurations when analyzed as either total sweat losses, % body weight loss, or sweat rate (Table 5). Analysis of sweat loss was not able to differentiate between evaporation and liquid sweat as much of the sweat loss occurred post-exposure during removal of the LA CPOG.

Mean skin temperatures were significantly lower during LA/LCV and SCAMP than LA-L/control across all subjects and generally lower than other configurations though these results were inconsistant among subjects. SCAMP generally maintained significantly lower ΔT_{thigh}, $\Delta T_{shin,}$ ΔT_{chest}, and ΔT_{arm} than other cooling systems (except LCV) in all subjects ($p<0.01$ in most cases). LCV also provided

significantly better than other cooling systems in minimizing ΔT_{chest} and ΔT_{arm} (generally $p < 0.01$) but results for ΔT_{thigh} and ΔT_{shin} were equivocal. HW consistantly produced significantly higher skin temepratures than the other runs ($P < 0.05$) while PCV results were inconclusive and more dependent on individual subject variations. Using either the LITPAC or SCBA did not significantly affect skin temperature changes. JSL runs produced significantly greater temperature increases in most runs

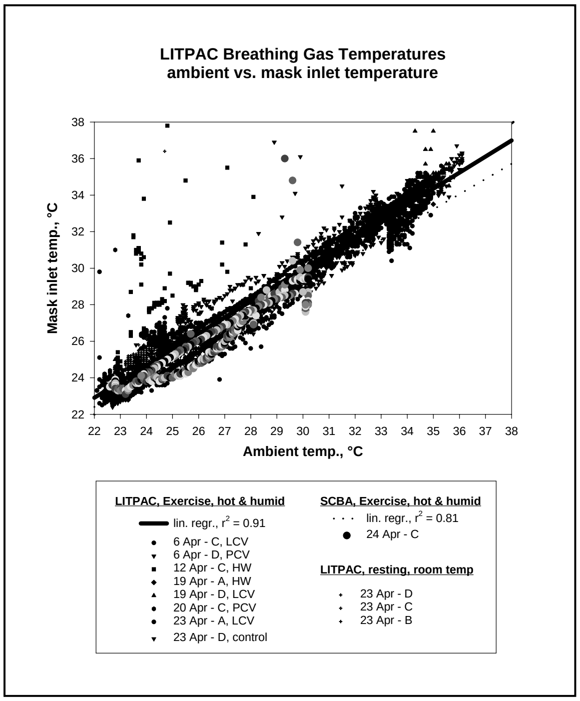

Figure 3. Relationship between breathing gas temperature and ambient temperature as a function of breathing system.

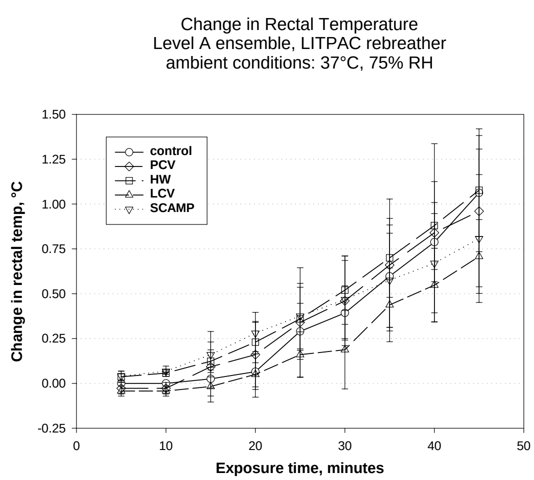

Figure 4. Rectal Temperature changes over time as a function of cooling system. Data is given as mean ± standard deviation.

Table 5. Observed subject tolerance and physiological temperature changes during experimental exposures.													
		Duration (minutes)			*Total Sweat Loss (kg)*				*% Weight Loss*				
	n	***mean***	***max***	***min***	***mean***	***max***	***min***	***SD***	***mean***	***max***	***min***	***SD***
LA-L/control	**4**	**45.8**	51	39	**0.87**	1.1	0.58	0.21	**1.1**	1.3	0.7	0.3
LA-L /HW	**3**	**43.1**	45	41	**4.78**	0.59	2.32	2.19	**2.8**	5.7	0.8	2.5
LA-L /LCV	**4**	**60.4**	87	40	**1.04**	1.49	0.69	0.39	**1.3**	1.8	0.9	0.5
LA-L /PCV	**4**	**49.2**	56	45	**0.56**	0.99	0.71	0.12	**1.1**	1.2	1.0	0.1
LA /SCAMP	**4**	**59.4**	72	33	**0.89**	0	1.46	0.71	**1.2**	2.0	0	0.9

compared to other configurations.HAILSS produced significantly lower ΔT_{chest} and ΔT_{arm} than most other configurations but essentially equivalent ΔT_{thigh} and ΔT_{shin} in the single individual tested.

<u>SUBJECTIVE RESPONSES</u>: No significant differences in comfort score sums were observed between configurations during the pre-exposure period or at the first rest period. A subjective ranking of cooling systems merit is given in Table 6. These responses reflect retrospective subjective assessments provided by the subjects at the end of the study and are not based on any quantitative analysis.

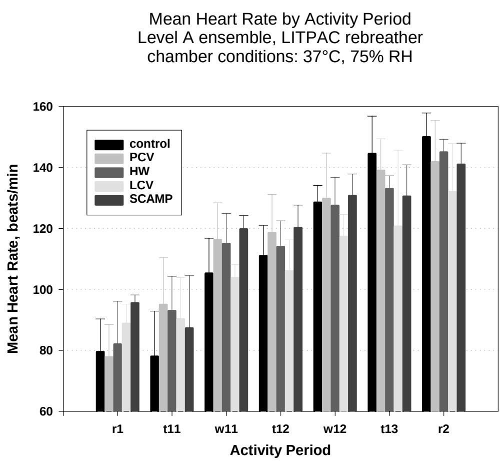

Figure 5. Mean heart rates measured at the end of each activity period as a function of cooling system (LA runs only). Data given as mean ± standard deviation.

<u>EQUIPMENT</u>: A number of equipment limitations and problems were detected during the course of the study. Most of these related to LCV and SCAMP hardware; HW and PCV were passive systems employing relatively simple technology. Both LCV and SCAMP cooling media provided for shorter exposure durations than initially anticipated. LCV ice containers typically lasted between 30-45 minutes before cooling became undetectable and needed replacement. In addition, one of the pump outlet hoses leaked after only 1-2 runs.

SCAMP bottles typically lasted approximately 30 minutes before requiring replacement, 50% less than an anticipated 60-minute duration. Furthermore, there were significant problems with initially charging the SCAMP bottle; leakage in the charging unit caused excessive use of liquid nitrogen and compressed air bottles. Even when repaired, the SCAMP recharging unit required a minimum of one “K” bottle of compressed medical grade air per SCAMP bottle.

Other problems encountered during SCAMP runs included a malfunctioning SCAMP monitoring meter. This meter generally posed a problem even prior to failure because the meaning of meter output was not well defined. A SCAMP air bottle inlet coupling also failed, leading to rapid depletion of available breathing gas and requiring a rapid swapping of bottles. Poor garment fit led to crimping in the inlet tubing of the SCAMP lower extremity tube suit and diminished leg cooling during that run.

A common problem was the extreme discomfort associated with the LITPAC and SCAMP support straps. Narrow straps and the attachment points on the units caused the straps to dig into a user's shoulders. In addition, subjects complained of the awkward position of the LITPAC weight on the back.

Table 6. Subjective cooling system ranking and overall comments following completion of study.

	Subject			
	A	**B**	**C**	**D**
Best	SCAMP	LCV	LCV	LCV
Worst	HW	HW	HW	HW
Subject comments	Given logistic considerations would prefer PCV	SCAMP worked best but not logistically feasible	Better training needed before using some systems	

DISCUSSION

None of the cooling systems tested in this study provided significantly greater protection in terms of extending exposure tolerance or minimizing the risk of heat injury. Physiological stress, as reflected in HR and salivary amylase data, also appeared unaffected by cooling system. Even overall comfort scores were unable to differentiate between cooling systems. HR and fatigue do reflect, however, the physical strain imposed by environmental conditions, physical tasks performed by subjects, and the burden of wearing heavy, bulky garments with additional weight imposed by cooling systems.

These equivocal results may reflect the severity of test conditions; wearing a LA in a hot/humid environment while exercising may overwhelm the cooling capacity of any of these systems. The intent of the study, however, was to identify cooling systems which might alleviate heat stress under the most dangerous environmental conditions by exposing subjects to extreme conditions. Dry bulb temperatures often exceed 37°C in much of the U.S. (e.g., approximately 5% of August days in Meridian, MS exceed 38°C (9)) so air temperatures used in the study are relatively conservative for a worst case scenario. The temperature/humidty combination used in this study is high (heat index (HI) = 144 (1)); only selected international geographic regions approach these combined high temperature/high RH on a regular, albeit uncommon, basis (e.g., Manama, Bahrain; Gwalior, India (2)). Humidity levels and consequently HI in the U.S. are typically lower but excursions approaching these levels can occur. This extreme hot/humid environment seems to reflect extreme but realistic conditions for CBIRF personnel wearing chemical protection and are the very conditions in which a cooling system becomes essential.

Humidity, however, should only affect heat exchange in vapor permeable garments; thermal conditions within the LA should be unaffected by ambient humidity because evaporation cannot occur across the impermeable material. Consequently, HI values are meaningless in assessing potential heat stress in individuals wearing impermeable clothing. This suggests a need for a new heat stress/strain index and exposure guidelines for users of impermeable clothing in hot environments.

Use of the LITPAC rebreather was feared to bias results because breathing gas gradually warms after repeatedly traversing the soda lime bed to extract CO_2. Using relatively cooler SCBA compressed air, however, did not mitigate T_{re} increases. It seems likely that heat transfer occurs as breathing gases travel from the gas source (LITPAC, SCBA) to the breathing mask because the gas is cooler than the surrounding atmosphere. Breathing gas warms as atmospheric heat is transferred to the tubing connecting the gas source and mask as noted in Figure 3. Inhaling this warm gas limits respiratory heat exchange and diminishes a potentially significant source of body cooling. Insulating SCBA tubing might mitage this problem by allowing cooler breathing gas to reach the respirator mask and improve overall body cooling. SCAMP potentially provides cooler air to the respirator though mask temperatures were not The large

number of runs terminated due to breathing related complaints suggests that breathing system improvements may provide tremendous benefits in extending tolerance of hot/humid environments.

A major goal of this study was to impose workloads and conditions which mirror field conditions. Subjects noted that the study workloads (treadmill walking, weight bearing) provided a reasonable approximation of field workload demands but dragging a heavier weight (approximately 50-100 kg) rather than bearing weights upright would better reflect field conditions. In addition, subjects noted that temperature and humidity were high but not unrealistic.

Liquid cooled systems (LCV, SCAMP) appeared to reduce skin surface temperatures but did not appreciably retard rising core temperatures. The general sense of approval given to LCV and SCAMP indicated in Table 8 probably reflects greater comfort due to lower skin temperatures. It was therefore surprising that comfort scores did not reflect these results and did not differentiate between configurations. These results do suggest that benefits from liquid cooling are generally independent of the source of cooling. SCAMP tended to produce somewhat cooler skin temperatures than LCV but generally their performance was similar. It is unclear whether the increased complexity of the SCAMP system is merited until a more detailed assessment of respiratory heat exchange is made. In contrast, passive cooling systems (PCV, HW) did not provide a noted improvement over the control condition of no cooling with regard to rectal or skin temperatures, HR, or comfort scores.

Sweat loss was also indistinguishable between cooling systems. Given similar thermal burdens represented by equivalent ΔT_{re}, sweat output would likely be equivalent. Cooling efficiency would improve if some of this sweat can evaporate. Unfortunately, none of the non-APACS cooling systems have any mechanism to actively extract water vapor from the microenvironment within a CPOG. Consequently, sweat loss during exposures depended entirely on diffusion which was impossible in the impermeable LA. Improving evaporative cooling in an impermeable CPOG has limited potential, however, because LCV, PCV, SCAMP, and HW depend on conduction as their primary heat exchange mechanism. While HW does employ evaporation, it is not evaporating sweat but using conductive heat exchange with the skin to evaporate water trapped in HW fibers.

One positive aspect of impermeable material was the insulation it apparently provided for roughly the first 20 minutes of exposure. Subjects had relatively low HR and ΔT_{re} at the first rest period during LA-L/control runs, probably reflecting relatively cool air trapped within the LA during dressing. This may suggest development of a variably permeable CPOG which can trap relatively cool air and passively extend exposure times.

CONCLUSIONS

1) None of the cooling systems provided a distinct advantage in the hot/humid environment with an imposed exercise regime. Consequently, individuals wearing impermeable garments in high heat/humidity conditions appear vulnerable to heat injury even when using one of the tested cooling systems. Defining heat exposure limits, therefore, appears necessary to provide some degree of protection against heat exhaustion and heat stroke for personnel wearing impermeable garments.

2) Passive cooling systems provide no apparent benefit over no cooling when used with an impermeable garment in extremely hot/humid environments. Liquid cooled systems may provide some benefit over no cooling but equivocal results suggest further study.

3) Breathing plays a major role in determine tolerance to hot/humid exposures. Choice of LA breathing system (LITPAC, SCBA), however, did not appear to affect outcome though the SCBA sample was very small.

4) Clear instructions and adequate training are required to avoid improper use of cooling systems. Inadequate quality control can hamper cooling system effectiveness.

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Inclusion of cooling systems in this study does not imply official or unofficial endorsement of these products in any way. The opinions expressed in this document reflect only the author's viewpoint and do not constitute an official position by the U.S. Navy, U.S. Marine Corps, Department of Defense, or other U.S. government agency.

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Individual Cooling Systems Results and Quantified Performances Using an Objective Method

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Summary

The evaluation of individual thermal assistance equipment can be quantified through numerous parameters. However, to assert efficiency and interest for a military user under tropical climate, it is necessary to follow a quantifying method.

This process of existing and prototyped measurements, based on simulations, with a dummy man and tests with voluntary subjects, using a scale of comparison. It has been clearly defined and used to evaluate of more as 10 systems, It allows to know the limits of each technology and the actual perspectives for equipment that are really suitable for the user.

This original method based on operational ergonomic and technical criteria take into account weight, efficiency linked with the work load, infrared and sound signature, life as well as the logistic needed for the use of these different equipment.

A complementary study of commercially available equipment, allows to compare and classify these equipment according to the same method. It allows the user to choose a suitable equipment to put eventually in service for overseas forces.

1. Introduction

The protection of human working in hazardous and extreme climatic conditions requires particular protective clothing. These equipment decrease the physical capabilities and the physiological ability to payload and could need a thermal assistance to allow the achievement of the mission.

Before testing in real scale on human, it is necessary to be sure of the reality and efficiency of the performances of the dedicated equipment. For this purpose, a progressive method has been previously described, using a thermal and instrumented manikin to measure the efficiency of thermal cooling systems and, in a second step, laboratory testing on human.

A testing procedure is still necessary to verify if the equipment can achieve the protection and cooling assistance requirement before their qualification.

2. Method

2.1. Suit insulation and cooling power measurement.

The measurement of the insulation of the thermal assistance suit is generally performed with a thermal manikin in specific conditions (after ASTM 1291-90).

The measurement system includes :
- a climatic chamber,
- an instrumented and thermal manikin, monitored by a computer.

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This method is well adapted to the quick measurement of clothing insulation (Clo) which is a characteristic of the suit and of the cooling system. It allows to measure the power really provided by the system to the manikin and eventually the response time due to thermal storage. By both measurement of the modification of suit insulation and of the powerful of the individual cooling system, the instrumented manikin is used in similar condition when measuring global suit insulation and thermal transfer.

The measurement protocol includes two successive steps. The first (15 minutes duration) is performed with the non operating thermal cooling system in order to measure the total insulation of equipment and the heating power of the manikin at thermal balance. The second, (variable duration according to the autonomy of the tested cooling device) is realised in normal operating mode of the system. The power modification in order to keep the thermal balance and the measurement of skin temperatures allow to characterise precisely the tested cooling system.

2.2. Laboratory test protocol on volunteers

The voluntary experimented people, regular soldiers, are informed on the interest of the experimentation.

Each people realise every two days in regular simulated tropical climatic environment (Ta= 35 °C, Hr= 40%, wind speed 1 m/s) the following protocol :

- 20 minutes of seated rest,
- 30 minutes of walk on a treadmill, (4 km/h, 0% slope)
- 10 minutes of seated rest
- 30 minutes of walk on a treadmill, (4 km/h, 0% slope)
- 30 minutes of seated recovery.

The trial begins by a reference test using protective equipment without any thermal assistance, and continue with the same suit plus the cooling equipment. The experimented people do not drink during the tests.

The physiological measurements include :

- rectal and skin temperature (Ramanathan method),
- cardiac signal and frequency issued from the cardiac signal,
- sweat loss and sweat weight fixed in each element of the suit,
- an evaluation using a questionnaire filled by the experimented people after each test.

2.3. Tested cooling devices

More as 10 different types of individual cooling system have been tested. The cooling process was a demonstrative panel of technologies using blowers with or without a complementary cooling device, such as ice packs (using water or CO^2), zeolite exchangers and gas compression systems. Transfer suit (jacket, 2 pieces undergarment) are specially designed for air or water circulation.

3. Results

By using laboratory data obtained with the thermal manikin, laboratory results on human, some times field trial results and for a few number of systems, information issued from scientific publications (non commercial data), the table of pertinent parameters is filled.

On the basis of these information, a first global and comparative report can be made, describing effective efficiency of each equipment. So it becomes possible to compare these final values with those provided by commercial equipment. The following tables give some information on technical characteristics and results concerning tested equipments.

All results were obtained with the same impermeable decontamination suit and with different individual cooling systems at 35°C and 40% relative humidity.

	Weight kg	**Total Power W**	**Autonomy min**	**Noise dBa**
Compression	10-13	120-160	40-120	65
Blowers	3.5-7	110-240	80-240	58
Ice packs	3-8	80-160	40-170	0-48
Zeolite-air	11-14	110-285	55-120	60-68

Table 1 : Main physical parameters of individual cooling systems.

	Effective power W	**Power/weight W/kg**	**Jacket Weight kg**	**Insulation Clo**
Compression	78-110	12-13	2.4-3.4	1.0-1.3
Blowers	95-220	31-47	0.65-1.10	0.80-0.95
Ice packs	95-150	26-53	1.6-6.2	0.79-1.0
Zeolite-air	55-235	8-25	1.00-1.10	0.98-1.2

Table 2 : Effective technical parameters of individual cooling systems.

	Effective power W	**Sweat loss kg**	**Sweat rate Kg/h**	**Thermal storage Kj/m²**
Compression	78-110	0.800	0.54	284
Blowers	95-220	0.83-1.20	0.5-0.55	225-270
Ice packs	95-150	0.55-1.2	0.39-0.53	274-330
Zeolite-air	55-235	1.15	0.54	220

Table 3 : Measured thermal parameters on human.

4. Conclusion

Using an instrumented thermal manikin and volunteers in laboratory, the measurements of the efficiency of individual thermal cooling systems has been performed. Through a very simple protocol, using dummy man, it allows to measure elementary parameters, like the modification of insulation due to the transfer jacket, the power really transferred to the user, and the autonomy. The test with the thermal and instrumented manikin is the indispensable preliminary step before trial on human in laboratory or on the field under extreme climatic ambience.

During laboratory testing on volunteers, heart rate, body temperatures and thermal storage measurement allow to determine employment security limits of these individual cooling systems.

Moreover this gradual method gives technical parameters that allow to compare different technologies of thermal cooling system in similar and easy to be reproduced conditions.

Comparing different technologies, cooling systems using blowers to favour sweat evaporation, give the best ratio “effective power/supplementary work load” accepted by man. Nevertheless new developments must involve advanced technologies in order to obtain good results in very hot and humid conditions.

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Human Adaptations to Heat and Cold Stress

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Summary

Heat acclimation consists of adaptations that mitigate physiological strain of heat stress, which improve thermal comfort and exercise capabilities. Adaptations are induced by repeated heat exposures that are sufficiently stressful to elevate core and skin temperatures and elicit perfuse sweating. Most adaptations to daily heat exposure occur during the first four days, and the remainders are complete by three weeks. Heat acclimation mediated adaptations include: lower core temperature, improved sweating and skin blood flow, lowered metabolic rate, reduced cardiovascular strain, improved fluid balance, and increased thermal tolerance (i.e., cellular stress protein adaptations). These adaptations vary somewhat depending if exposed to dry or humid heat.

Adaptations to chronic cold exposure can be categorized into three basic patterns: habituation, metabolic adaptations and insulative adaptations. The exact determinant of which pattern will be induced by chronic cold exposure is unclear, but the magnitude and extent of body cooling, frequency and duration of exposure, and individual factors all influence the adaptive process. Habituation is characterized by blunted shivering and cutaneous vasoconstriction; body temperature may decline more in the acclimatized than unacclimatized state. It is the most common cold adaptation and results from periodic short-term cold exposures. Metabolic adaptations are characterized by enhanced thermogenesis that develops when cold exposures are more pronounced, but not severe enough to induce significant declines in core temperature. Insulative adaptations are characterized by enhanced vasoconstriction and redistribution of body heat toward the shell that develops from repeated cold exposures severe enough to induce marked declines in core temperature.

Introduction

Humans encounter thermal (heat & cold) stress from climatic conditions, insulation worn and body heat production. Alterations in body temperatures (skin, muscle & core) above and below "normal" levels can degrade exercise performance and cause thermal injury. Humans regulate core temperature within a narrow range (35^{o} to 41^{o}C) through two parallel processes: physiological and behavioral temperature

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regulation. Physiological temperature regulation operates through responses that are independent of conscious voluntary behavior, and includes control of: a) rate of metabolic heat production, b) body heat distribution via the blood from the core to the skin, and c) sweating. Behavioral temperature regulation operates through conscious behavior, and includes actions such as modifying activity levels, changing clothes and seeking shelter. For humans, physiological thermoregulation is most important during heat stress and behavioral thermoregulation is most important during cold stress.

Human demonstrate adaptations to repeated exposure to either heat (85) or cold (105) stress. In general, these adaptations act to defend body temperatures, reduce physiologic strain, and improve comfort / work capabilities and reduce susceptibility to thermal injury. This paper examines human thermoregulation and adaptations to repeated heat or cold stress. Throughout this paper, the terms acclimation and acclimatization will be used interchangeably. Acclimatization develops from challenges in the natural environment, and acclimation develops from experimental exposure to artificial conditions, both elicit similar adaptations. However, acclimatization can reflect adaptations to stimuli besides thermal strain, such as diet and activity level.

Adaptations to Heat Stress

Humans have remarkable ability to adapt to heat stress, and given adequate water and protection from the sun, a healthy acclimated persons can tolerate extended exposure to virtually any natural weather-related heat stress (85,97). Heat stress results from the interaction of environmental conditions (temperature, humidity, sun), physical work rate (body heat production) and wearing of heavy clothing / equipment that impedes heat loss. Environmental heat stress and exercise interact synergistically to increase strain on physiological systems (66). This strain is manifested by high skin and core temperatures, excessive cardiovascular strain and reduced performance. Heat acclimation results in biological adaptations that reduce these negative effects of heat stress. One becomes acclimated to the heat through repeated exposures that are sufficiently stressful to elevate both core and skin temperatures and provoke perfuse sweating. These biological adaptations occur from integrated changes in thermoregulatory control, fluid balance, and cardiovascular responses

Induction & Decay. The magnitude of biological adaptations induced by heat acclimation depends largely on the intensity, duration, frequency and number of heat exposures (85). Exercise in the heat is the most effective method for developing heat acclimation, however, even resting in the heat results in some acclimation. The full development of exercise-heat acclimation does not require daily 24-h exposure. A continuous, daily 100-min period of exposure appears to produce an optimal heat acclimation response in dry heat (57). Studies examining heat acclimation have generally used daily heat exposures; however, these are not necessary to produce heat acclimation. Fein and colleagues (20) examined the time course of biological adaptations to 10 days of heat exposure, when subjects were exposed to heat (47°C, 17% relative humidity) daily or every third day. Therefore, one group completed the acclimation program in 10 days and the other in 27 days. Both methods were equally effective in producing heat acclimation, but with daily heat exposures it required only one-third of the total time.

Heat acclimation is transient, it gradually disappears if not maintained by repeated heat exposure. The heart rate improvement, which develops more rapidly during acclimation, is also lost more rapidly than thermoregulatory responses. There is no agreement concerning the rate of decay for heat acclimation. Lind (56) believed that heat acclimation might be retained for two weeks after the last heat exposure, and then be rapidly lost over the next two weeks. Williams and colleagues (98) report some loss of acclimation in sedentary individuals after one week, with the percentage loss being greater with increasing time; and, by three weeks losses of nearly 100% for heart rate and 50% for core temperature. Physically trained and aerobically fit persons may retain benefits of heat acclimation longer (73).

Actions & Mechanisms. Table 1 provides a brief description of the actions of heat acclimation (86). Heat acclimation improves thermal comfort and submaximal exercise performance. These benefits of heat acclimation are achieved by improved sweating and skin blood flow responses, better fluid balance and cardiovascular stability, and a lowered metabolic rate (41,85).

Heat acclimation does not improve maximal intensity exercise performance. For example, heat stress mediated reductions in maximal aerobic power are not abated by heat acclimation (87). In addition, heat acclimation does not alter the maximal core temperature a person can tolerate during exercise in the heat (69,70). There is evidence, however, that persons who live and train over many weeks in the heat might be able to tolerate higher maximal core temperatures than persons heat acclimated over one or two weeks (82). Other studies (26,75) suggest that successful hot-weather athletes may be able to tolerate higher core temperatures.

Table 1 - Actions of Heat Acclimation (86)

Thermal Comfort – Improved	**Exercise Performance – Improved**
Core Temperature – Reduced	**Cardiovascular Stability – Improved**
Sweating – Improved	Heart Rate - Lowered
Earlier Onset	Stroke Volume – Increased
Higher Rate	Blood Pressure – Better Defended
Redistribution (Tropic)	Myocardial Compliance - Improved
Hidromeiosis Resistance (Tropic)	**Balance - Improved**
Blood Flow - Increased	Thirst - Improved
Earlier Onset	Electrolyte Loss – Reduced
Higher Flow	Total Body Water – Increased
	Plasma Volume – Increased & Better Defended
Metabolic Rate – Lowered	

Heat acclimation mediates improved submaximal exercise performance by reducing physiologic strain during exercise. The three classical signs of heat acclimation are lower heart rate and core temperature, and higher sweat rate during exercise-heat stress. Skin temperature is lower after heat acclimation than before, and thus dry heat loss is less (or, if the environment is warmer than the skin, dry heat gain is greater). To compensate for the changes in dry heat exchange, there must be an increase in evaporative heat loss, in order to achieve heat balance. After acclimation, sweating starts earlier and at a lower core temperature, i.e., the core temperature threshold for sweating is decreased. Sweating rate is usually increased by the second day of heat acclimation (17,27,70,96,101). The sweat glands also become resistant to hidromeiosis and "fatigue" so that higher sweat rates can be sustained. Earlier and greater sweating improves evaporative cooling (if the climate allows evaporation) and reduces body heat storage and skin temperature. Lower skin temperatures will decrease the skin blood flow required for heat balance (because of greater core-to-skin temperature gradient) and reduce skin venous compliance so that blood volume is redistributed from the peripheral to the central circulation. All of these factors reduce cardiovascular strain and enhance exercise-heat performance.

On the first day of exercise in the heat, heart rate reaches much higher levels than in temperate conditions, and stroke volume is lower. Thereafter, heart rate begins to decrease as early as the second day of heat acclimation. These changes are rapid at first, but continue more slowly for about a week. There are probably numerous mechanisms that participate, and their relative contributions will vary, both over the course of the heat acclimation program and also among subjects (85,97). These mechanisms include: a) improved skin cooling and redistribution of blood volume (81); b) plasma volume expansion (90); c) increased venous tone from cutaneous and non-cutaneous beds (99);and d) reduced core temperature (85). In addition, myocardial changes reported from heat acclimatization include increased compliance (44) and isoenzymes transition reducing the myocardial energy cost (43).

The effects of heat acclimation on stroke volume and cardiac output responses to exercise-heat stress are not clear-cut. For example, two studies (78,101) report increased stroke volume with little change in cardiac output as heart rate fell; but another study (100) reports a decrease in cardiac output, associated with a decrease in "surface blood flow" (estimated calorimetrically) as heart rate fell, and little change in stroke volume; and still another study (102) reports a mixed pattern, with two subjects showing a steady increase in

stroke volume, one a transient increase, reversing after the sixth day, and one showing no increase. The reason for these differences is not clear: Rowell et al. (78) describe dry heat acclimation, and Wyndham (101) and Wyndham and colleagues (101,102) all describe humid heat acclimation.

Nielson and colleagues (69,70) examined stroke volume responses during exercise before and after heat acclimation. One study (69) had subjects acclimate for 9-12 days in hot-dry conditions while performing cycle ergometer (60%VO_{2max}) exercise. They reported that during exercise, heat acclimation increased stroke volume and increased cardiac output (~1.8 L/min). The other study (70) had subjects acclimate for 8-13 days in hot-humid conditions while performing cycle ergometer (60%VO_{2max}) exercise. They reported that during exercise, heat acclimation did not alter stroke volume or cardiac output. Both studies reported plasma volume expansion of 9 to 13% with heat acclimation. It seems possible that dry and wet heat acclimation usually increased stroke volume responses, but that improved cardiac output responses are more likely to be observed with dry heat acclimation.

Heat acclimation can alter whole-body (85) and muscle metabolism (103). The oxygen uptake response to submaximal exercise is reduced by heat acclimation (83). Consistent with this is the observation that basal metabolic rate is decreased during warmer months (41). Lactate accumulation in blood and muscle during submaximal exercise is generally found to be reduced following heat acclimation (107). King et al. (50) and Kirwan et al. (51) both observed that heat acclimation reduced muscle glycogen utilization during exercise in the heat by 40-50% compared to before acclimation. Young et al. (107) also observed a significant glycogen-sparing effect due to heat acclimation, but the reduction in glycogen utilization was small, and apparent only during exercise in cool conditions. Glycogen utilization during exercise in the heat was negligibly affected.

Fluid Balance & Blood Volume. Fluid balance improvements from heat acclimation include better matching of thirst to body water needs, reduced sweat sodium losses, increased total body water and increased blood volume (59,81). Thirst is not a good index of body water requirements as *ad libitum* water intake results in incomplete fluid replacement or “voluntary” dehydration during exercise-heat stress. Heat acclimation improves the relationship of thirst to body water needs so that “voluntary” dehydration is markedly (~30%) reduced (7,17). Therefore, heat acclimated persons will dehydrate less during exercise in the heat, provided that access to fluids is not restricted. This is an important adaptation as heat acclimation increases sweating rate and if fluid replacement is not proportionately increased then greater dehydration will occur.

Most studies report that heat acclimation increases total body water (81). The magnitude of increase ranges from 2.0 to 3.0 liters or ~ 5% to 7% of total body water. This increase is well within the measurement resolution for total body water (81) and thus appears to be a real physiological phenomenon. The division of the total body water increase between intracellular fluid (ICF) and extracellular fluid (ECF) is variable: studies report that ECF accounts for greater, equal and smaller than its percentage increase in total body water after heat acclimation (81). Measures of ECF have relatively high variability, and therefore trends for such small changes are difficult to interpret. The extent of which ICF increases is unclear because typically it is calculated as the difference between total body water and ECF, and thus measurement variability inherent in both these techniques is compounded in the calculation of ICF. If total body water and ECF increase after heat acclimation, then expansion of blood volume might be expected.

Heat acclimation increases blood volume through differential effects on erythrocyte and plasma volumes. Erythrocyte volume does not appear to be altered by heat acclimation or season (80). Plasma volume expansion is usually, but not always, present after repeated heat exposure and heat acclimation (81). Heat acclimation studies report that plasma volume expansion, generally ranged from 0% to 30%, and the magnitude of increase is somewhat dependent on whether the person is at rest or performing exercise, the heat acclimation day and the hydration state when measurements are made (79). Plasma volume expansion seems to be greatest when performing upright exercise on about the fifth day of heat acclimation and when fully hydrated.

The mechanism(s) responsible for this hypervolemia are unclear, but may include an increase in extracellular fluid mediated by retention of crystalloids (primarily sodium chloride) and perhaps an increase in plasma volume selectively mediated by the oncotic effect of intravascular protein (58,59). Heat acclimated persons also exhibit a more stable plasma volume and more consistent intravascular fluid response to exercise-heat stress than do persons who are not heat acclimated (79). The increase in total body

water can be explained in part by increased aldosterone secretion and / or renal sensitivity to a given plasma concentration. Francesconi and colleagues (23) have shown that exercise - heat exposure markedly increased plasma aldosterone concentration which was subsequently abated by heat acclimation.

An unacclimatized person may secrete sweat with a sodium concentration of 60 meq•L^{-1} or higher and therefore, if sweating profusely, can lose large amounts of sodium. With acclimatization, the sweat glands become able to conserve sodium by secreting sweat with a sodium concentration as low as 10 meq•L^{-1}(1). This salt-conserving effect of acclimation depends on the adrenal cortex; and aldosterone, which is secreted in response to exercise and heat exposure as well as to sodium depletion, appears to be necessary for its occurrence. The conservation of salt also helps to maintain the number of osmoles in the extracellular fluid, and thus to maintain or increase extracellular fluid volume (71).

Dry vs Humid Heat. Although heat acclimation in a dry environment confers a substantial advantage in humid heat, the physiological and biophysical differences between dry and humid heat lead one to expect that humid heat acclimation would produce somewhat different physiological adaptations from dry heat acclimation; and although the pertinent literature is rather meager, there is evidence to support this expectation.

Fox et al. (22) compared the effects of acclimation to dry and humid heat on the inhibition of sweating. They acclimated resting subjects with controlled hyperthermia, maintaining core temperature near 38.2°C for 2 hours a day for 12 days, using dry heat for one group and moist heat for the other group. To collect sweat, both groups had their left arms in plastic bags, which created a warm, humid microclimate. After acclimation both groups showed similar decreases in heart rate and core and skin temperatures, with similar increases in sweating during an exercise-heat test. In a 2-hour controlled hyperthermia test while they rested in very humid heat, both groups had about the same whole-body sweat rates. The arms that were exposed to humid heat during acclimation had—compared to pre-acclimation responses—similar and large increases in their sweat production during this test, and sweat rates of these arms declined more slowly during the test. During the same test the right arms of the "dry" group, which had not experienced humid heat during acclimation, also had a higher initial sweat rate than before acclimation, but thereafter their sweat rate declined as fast as before acclimation, so that their total sweat secretion during the test was substantially less than that either of the contralateral arms or of the arms of the "humid" group. Thus most of the improvement in the ability to maintain high sweat rates in high humidity after acclimation apparently owed to a diminution of hidromeiosis.

Strydom and Williams (95) tested subjects' responses to 4 h of exercise in a humid environment both before and after a program of physical training, and compared their responses to those of another group of subjects who were well acclimated to humid heat. During the first hour of exercise, subjects in the training group showed better heat tolerance after training than before; and their responses after training approached those of the well-acclimated group. During the second hour of exercise, however, their heart rates and rectal temperatures increased more than those responses for the heat acclimated subjects, and by the end of the second hour their responses after training had come to appear more like their responses before training, and less like the responses of the heat acclimated subjects. Except during the first hour of the exercise-heat exposure, the physically trained subjects sweated considerably less than the heat acclimated subjects. Therefore, the probable reason for the greater physiological strain that the physically trained subjects experienced in the second hour and beyond was their inability to secrete and evaporate sweat at a rate sufficient to achieve thermal balance.

To achieve a high evaporative cooling rate in a humid environment, it is necessary to overcome the high ambient water vapor pressure by maintaining either a higher vapor pressure at the skin (which requires a higher skin temperature) or a larger wetted skin area, as compared to what would be necessary in a dry environment. Unless core temperature is allowed to rise along with skin temperatures, the higher skin temperature must be achieved by increasing core-to-skin thermal conductance, which requires a higher skin blood flow. Therefore, one expected difference between acclimation to humid heat and acclimation to dry heat is for the former to involve greater circulatory adaptations, to support higher skin blood flow with minimal circulatory strain.

Another difference that might be expected between acclimation to humid heat and dry heat is for the former to enable more efficient use of the skin as an evaporating surface. In humid heat, a greater portion of the sweat production is on the limbs after acclimation than before (85). We are not aware of any reports of

changes in the regional distribution of sweating after acclimation to dry heat. Before acclimation, mean sweating intensity (i.e., sweat rate per unit area) is much lower on limbs than on the trunk, so acclimation tends to make the sweating intensity more uniform over the skin surface. This is an advantage in humid heat, because it increases the wet body surface area, and therefore sweat evaporation rate, and probably reduces the extent to which sweating in some regions is in excess of the rate it can be evaporated.

Research has not fully evaluated the magnitude of cross-acclimation that exercise combined with either dry or humid heat confers during exercise in the other hot climate. Studies indicate (which generally have inadequate designs and limited data) that some cross acclimation can occur between humid heat and dry heat exposure. Passive dry heat or passive humid heat acclimation elicited similar core temperature levels during exercise in both hot climates (21). Exercise-dry heat acclimation conferred an advantage (over no heat acclimation) during exercise in humid heat (7,21) and vice versa (16). In addition, Shapiro and colleagues (91) reported that exercise (~35% VO_{2max})-dry heat acclimation elicited equal or greater core temperature during exercise in humid heat than a matched (WBGT = 34^{o}C) dry heat climate. Unfortunately, that study did not report pre-acclimation data and employed only dry heat acclimation. Sawka and colleagues (84) found that exercise (~29% VO_{2max}) in matched (WBGT -32^{0}C) hot-dry and hot-wet climates resulted in similar core temperature levels both before and after completing a heat acclimation program (which consisted of daily alternating dry heat and humid heat exposures).

Griefahn and Schwarzenau (28) compared the physiologic time course of acclimation to humid-heat, dry-heat and radiant-heat at equivalent (33^{o}C) WBGT temperatures. Eight subjects complete a 15-day exercise heat acclimation program in each climatic condition. An unknown number of subjects participated in one to all three of the heat acclimation programs that were spaced by at least 52 days. These investigators reported that humid-heat elicited a more rapid acclimation and less physiologic strain (core temperature, heart rate and sweating rate) than dry-heat exposure. Unfortunately, the experimental design (lack of matched groups or cross over testing) did not allow cross acclimation effects' to be evaluated nor did the authors speculate their findings to that issue.

No study directly compared deacclimation for matched groups after humid heat and dry heat acclimation. Pandolf and colleagues (73) acclimated soldiers to dry heat (49^{o}C, 20%) and studied their deacclimation over 3-weeks. They reported that 13% and 4% of the core temperature 'advantages, and 23% and 29% of the heart rate advantages were lost after one and three weeks of deacclimation, respectively. Williams and colleagues (98) acclimated African miners to humid heat (35^{o}C, 80%) and studied their deacclimation over three weeks. They reported that 26% and 45% of the core temperature advantages and 65% and 92% of their heart rate advantages were lost after one and three weeks of deacclimation, respectively. Together these studies suggest that deacclimation might occur more rapidly for humid than dry heat.

Aerobic Fitness. In addition to improving aerobic power, endurance training in temperate climates reduces physiological strain and increases submaximal exercise capabilities in the heat and endurance-trained individuals exhibit many of the characteristics of heat-acclimated individuals during exercise in the heat (5). In addition, aerobically fit persons develop heat acclimation more rapidly than less fit persons, and high aerobic fitness might reduce susceptibility to heat injury / illness (25). A person's maximal aerobic power accounts for approximately 44% of the variability in core temperature after 3 h of exercise in the heat, or the number of days required for complete development of heat acclimation (5). However, endurance training alone does not totally replace the benefits of heat acclimation produced by a program of exercise in the heat (5).

Some investigators believe that for endurance training to improve thermoregulatory responses during exercise in the heat, the exercise training sessions must produce a substantial elevation of core temperature and sweating rate. Henane and colleagues (33) compared thermoregulatory responses of six skiers (VO_{2max} =67 ml•kg^{-1}•min^{-1}) with those of four swimmers (VO_{2max} = 66 ml•kg^{-1}•min^{-1}), found that skiers were more heat tolerant and better acclimatized than swimmers, and attributed the difference to a smaller increase in the swimmers' core temperature produced during training in cold water. In agreement, Avellini et al. (6) found that four weeks of training by cycle exercise in 20^{o}C water increased VO_{2max} by 15%, but did not improve thermoregulation during exercise-heat stress. Thus, high VO_{2max} is not always associated with improved heat tolerance.

To achieve improved thermoregulation from endurance training in temperate climates, either strenuous interval training or continuous training at intensities greater than 50% VO_{2max} should be employed. Lesser training intensities produce questionable effects on performance during exercise-heat stress (5). The endurance training must last at least one week (67) and some authors show that the best improvements require 8-12 weeks of training (5).

Thermal Tolerance. Thermal tolerance refers to cellular adaptations from a severe nonlethal heat exposure that allows the organism to survive a subsequent and otherwise lethal heat exposure (42,64). Thermal tolerance and heat acclimation are complimentary as acclimation reduces heat strain and tolerance increases survivability to a given heat strain. For example, rodents with fully developed thermal tolerance can survive 60% more heat strain than what would have been initially lethal (60). Thermal tolerance is associated with heat shock proteins (HSP) binding to denatured or nascent cellular polypeptides and providing protection and accelerating repair from heat stress, ischemia, monocyte toxicity, and UV radiation in cultured cells and animals. HSPs are grouped into families based upon their molecular mass. These HSP families have different cellular locations and functions that include processing of stress-denatured proteins, management of protein fragments, maintenance of structural proteins, and chaperone of proteins across cell membranes.

The HSP responses will increase within several hours of the stress and will last for several days after the exposure. After the initial heat exposure, mRNA levels will peak within an hour and subsequent HSP synthesis depends upon both severity of heat stress and cumulative heat stress imposed (60). Both passive heat exposure and physical exercise will elicit HSP synthesis; however, the combination of exercise and heat exposure elicits a greater HSP response than either stressor does independently (93). Recent research has identified ~130 genes that are up-regulated and ~89 genes down-regulated during heat stress (24). The contribution of most of these genes on thermal tolerance has not been determined, but certainly more then HSP responses are involved.

Adaptations to Cold Stress

Human thermoregulatory adaptations to chronic cold exposure are more modest and less understood than adaptations to chronic heat (104). Where chronic heat exposure induces a fairly uniform pattern of thermoregulatory adjustments, chronic cold exposure induces three different patterns of adaptation. Habituation is characterized by blunted physiological responses during cold exposure. Metabolic adaptations are characterized by enhanced thermogenic responses to cold. Insulative adaptations are characterized by enhanced body heat conservation during cold exposure.

Habituation. Habituation, the most commonly observed cold adaptation, is characterized by blunted shivering, blunted cutaneous vasoconstrictor response, or both. Circumpolar residents such as the Inuits (2,32,35), other Native North Americans from the Arctic (18,45) and Norwegian Lapps (3) respond to whole-body cold exposure in a similar manner as persons from temperate climates. That is, metabolic heat production increases due to shivering, and convective heat loss decreases due to vasoconstriction of peripheral blood vessels. However, these responses may be less pronounced in circumpolar residents, as demonstrated in studies of Norwegian Lapps (3). The Lapps exhibited a smaller increase in oxygen uptake, indicative of less shivering, compared to control subjects. Lapps also maintained warmer skin during cold exposure than unacclimatized persons. Other circumpolar residents also exhibited blunted shivering (2) and blunted vasoconstrictor responses to cold (35,77) compared to control subjects.

The warmer skin in cold-exposed circumpolar residents than control subjects results from altered vasomotor responses. Inuits maintained higher hand blood flow than unacclimatized subjects during two-hour water immersions at temperatures ranging from 45^{o}C down to 5^{o}C, and the difference was greatest at the colder temperatures (12). Elsner *et al.* (19) observed that during hand immersion in cold water Native Americans from the arctic exhibited greater hand heat loss than unadapted control subjects. Forearm blood flow during arm immersion in cold water was greater in Inuits than control subjects (11). Collectively, these observations indicate that cold-induced vasoconstriction is less pronounced in circumpolar residents than in unacclimatized persons.

The blunted shivering and vasonconstrictor responses that develop with habituation, might lead to a greater fall in core temperature during cold exposure. This is evident in the studies of the Lapps, however, not all cold habituated circumpolar residents manifest hypothermic habituation. Americans native to Arctic regions and unacclimatized subjects do not differ in core temperature response to cold exposure (2,32,35,45,77).

The blunted response to cold is less apparent in young circumpolar residents suggesting that the adaptation is developed over time rather than inherited (63). Also, other ethnic groups from temperate climates whose occupations necessitate frequent cold exposure of the hands, and people who sojourn in circumpolar regions experience cold habituation (9,10,13,54,62,68), even when those cold exposures are rare and brief (10,62). Thus, habituation can occur even when cold exposures are too mild or brief to cause increased body heat loss or a fall in body temperature. Cold acclimation studies confirm this suggestion.

Attempts to induce cold acclimation by repeated cold-air exposure have employed a wide range of temperatures and exposure durations. Brief ($\leq$ 1-hr) cold air exposures, repeated over a two-week period, resulted in blunted shivering but had no effect on body temperature during cold exposure (4,34,92). In studies employing longer exposure durations and a longer acclimation period, reduced shivering was accompanied by blunted vasoconstriction (61). Habituation of both shivering and vasoconstrictor responses can lead to more pronounced declines in body temperature during cold exposure than occur in unadapted persons exposed to the same conditions (14,49,52). Hence, this is termed hypothermic habituation.

Superficially, habituation may not seem beneficial since the thermoregulatory adjustments do not help maintain normal body temperature during cold exposure. However, people living in regions experiencing the most extreme cold weather on earth generally have adequate clothing and shelter to protect them from the cold, so they probably do not experience significant whole-body cooling, thus, explaining the lack of more dramatic thermoregulatory adjustments. On the other hand, periodic short-term exposure of small portions of the body would be common, such as when gloves are removed to complete a task requiring dexterity or when individuals moved through unheated corridors of a polar base. Indeed, when whole body cooling is unlikely, warmer skin and reduced shivering would help conserve energy, improve comfort and prevent peripheral cold-injuries.

Metabolic Adaptations. Thermoregulatory responses to cold in the Alacaluf people have been cited as evidence for a metabolic cold adaptation (29,30). These nomadic Native Americans lived on coastal islands off the southern tip of South America, where the climate was rainy and cool (lows from 0 to 8^{o}C and highs from 5 to 15^{o}C). Overall, when they were studied for signs of cold acclimatization, the Alacaluf's way of life was similar to Inuits of the North American Arctic. While the environment was less severe, the Alacaluf's clothing (loin cloth and cloak) and shelter (lean-tos built from scrap lumber) were less protective than that of the Inuits.

During a standardized overnight cold exposure, Hammel et al. (30) observed that metabolic heat production was initially higher in Alacaluf than unacclimatized subjects. Some researchers consider this evidence of enhanced thermogenesis, or metabolic acclimatization, induced by chronic cold. However, in contrast to the progressive rise in metabolic heat production exhibited by unacclimatized subjects during the overnight cold exposure, Alacaluf subjects exhibited a progressive fall in heat production, so that the Alacaluf and non-adapted subjects reached similar metabolic rates by the end of the cold exposure (30). Therefore, these people may, in fact, have been exhibiting effects of cold habituation (i.e. blunted shivering) rather than an enhanced thermogenic response.

One other study suggests that an enhanced metabolic response to cold can develop due to repeated cold exposure. Scholander *et al.*(88) studied eight students who camped six weeks in the Norwegian mountains during autumn when it was moderately cold, and rain, sleet and snow were frequent. To increase cold stress, the students had only lightweight summer clothing and minimal shelter. After completing this acclimation period, the campers exhibited a greater increment in metabolism upon cold exposure than unadapted subjects. However, Scholander *et al.* (88) failed to measure the responses before the campers underwent the acclimation. It is unclear whether control and acclimation groups were matched for confounding factors such as body composition, physical fitness or age. Therefore, the possibility that repeated cold exposure humans can induce enhanced thermogenic response remains open to question.

Insulative Cold Adaptations. Studies of the Aborigines living in the central Australian desert suggested an insulative pattern of cold acclimatization (31,36,89). Night-time lows in the central Australian desert reach 0°C in winter and 20°C in summer; low humidity and clear atmosphere facilitated evaporative and radiative cooling. When these studies were being completed, the central Australian Aborigines were nomadic people who lived out of doors and wore no clothing. They slept on bare ground and their only protection from the cold was a small fire at their feet and windbreak made from light brush.

While metabolic rate increased in unadapted European subjects sleeping in the cold, the Aborigine's metabolic rate remained unchanged as ambient temperature fell at night (29,36,89). In contrast to habituated circumpolar residents, the Aborigines exhibited a greater fall in skin temperature than did Europeans which was attributed due to a more pronounced cutaneous vasoconstrictor response to cold (36,89). Additionally, the Aborigine's rectal temperature also fell more than in control subjects (31). However, thermal conductance (metabolic heat production divided by the core to skin temperature gradient) was less in the Aborigine than unacclimatized Europeans suggesting that the lower thermal conductance of the Aborigine reflected an enhanced vasoconstrictor response to cold. Alternatively, the Aborigines may have exhibited a lower thermal conductance simply because their shivering had become habituated, but unlike the Inuits and Lapps, vasoconstrictor responses had not.

Long-distance swimmers, surfers and scuba divers show a blunted or delayed shivering during cold-water immersion (15,94) suggesting that they have become cold habituated. However, studies of professional breath-hold divers of Korea, the Ama, and their counterparts in Japan, suggest development of a more complex adaptation to repeated cold-water immersion. Traditionally, the divers wore only a light-weight cotton bathing suit which offered little insulation, and they dove year round in water as cold as 10°C in the winter and 25°C in the summer (39,40). During these dives, they experienced marked whole-body cooling. The divers continued working in the water until their core temperature fell by 2°C (47,48). These people’s willingness to repeatedly subject themselves to such stressful conditions alone seems evidence for their acclimatization to cold.

Kang et al. (46) observed that Korean diving women exhibited a seasonal variation in basal metabolic rate (BMR) consistent with a metabolic acclimatization. In the summer, when water temperatures were warmest, the Ama's BMR was lowest. Throughout the fall, the Ama's BMR increased, becoming highest in the winter when water temperatures were coldest. Non-diving control subjects from the same community exhibited no seasonal fluctuation in BMR. While the elevated BMR during winter appeared related to increased cold stress, the practical value of an increased BMR was negligible (39,46). Other observations are consistent with the development of cold habituation in the diving women. The Korean diving women tolerated much colder water without shivering than non-divers of comparable fat thickness (37,38). Although the Ama's shivering responses indicate that they had become cold-habituated, their vasomotor responses and skin heat flow during cold exposure suggest that a more complex acclimatization.

The Ama diving women appeared to have developed an insulative form of cold acclimatization; that is, mechanisms for body heat conservation were enhanced. Maximal tissue insulation was greater in divers than in non-divers with comparable subcutaneous fat thickness (38). The mechanisms for the insulative acclimatization remain unidentified. However, assuming that skin thickness contributes negligibly to insulation, the increased insulation in divers must derive from their control of circulation to the peripheral shell.

Unfortunately, follow-up studies are no longer possible. Since 1977, the divers have used wet suits, and modern divers have substantially more subcutaneous fat than the first diving women studied (74). Thus, modern divers experience less body cooling than traditional divers and insulative acclimatization is no longer apparent (74). This suggests that the stimulus for the different pattern of cold acclimatization exhibited by the traditional divers as opposed to circumpolar residents or Aborigines was the more substantial whole-body cooling experienced by the traditional divers. Acclimation studies tend to support this thesis.

Repeated cold-water immersion induces different acclimation patterns, depending on cold intensity, exposure duration and length of acclimation period. Brief immersions induce habituation, even when only a few immersions are completed (53,55,76). For example, Radomski and Boutelier (76) had subjects immerse themselves in 15°C water 20-60 minutes a day for 9 days, and observed shivering and vasoconstrictor responses to cold became blunted, allowing a greater fall in rectal temperature. This hypothermic habituation

also diminished the sympathetic response to cold. When the immersion durations are increased and the immersions repeated over a longer acclimation period, acclimation patterns besides habituation are induced.

Young et al. (105,106) studied the effects of an acclimation program consisting of 90 minutes of immersion in 18^{o}C water, repeated five days per week for eight weeks. During each immersion, subjects experienced about a 1^{o}C decrease in rectal temperature. Before and after acclimation, physiological responses were measured while the subjects were exposed to cold (5^{o}C) air. Some acclimation effects appeared consistent with hypothermic habituation. Metabolic heat production increased more slowly during cold-air exposure following acclimation, and the fall in rectal temperature during cold-air exposure was greater and more rapid. However, other adaptations suggested the development of an insulative acclimation.

Following repeated cold-water immersion, cold-air exposure caused skin temperature to fall about 4^{o}C lower than before acclimation (105). The greater fall in skin temperature during cold exposure suggests that a more pronounced cutaneous vasoconstrictor response to cold had developed. The increment in plasma norepinephrine concentration elicited by cold air exposure was more than two-fold greater following acclimation suggesting increased sympathetic nervous responsiveness to cold. In addition, a smaller increment in blood pressure during cold exposure was observed after acclimation, while cardiac output responses to cold were unaffected (65). The blunting of the systemic pressure response to cold indicated that subcutaneous vascular beds are better perfused following acclimation. Thus, as was suggested to have occurred in the Korean diving women, acclimation by repeated cold-water immersion may enable better heat conservation by improved insulation at the shell surface, while perfusion of the subcutaneous shell is more optimally maintained than before acclimation.

The lower skin temperatures during cold air exposure following acclimation (9,105) have two implications. First, at a given air temperature, lower skin temperatures reduce the thermal gradient for heat transfer between skin and air, which improves insulation. Second, the magnitude of the acclimation effect on skin temperature maintained during cold exposure exceeds the magnitude of the acclimation effect on core temperature maintained during cold air exposure. Therefore, the core-to-skin thermal gradient is enlarged. A larger thermal gradient between core and skin would favor redistribution of body heat from the core to the subcutaneous muscle shell, while lower skin temperature due to enhanced cutaneous vasoconstriction in cold air would limit heat loss from the body's shell.

Recently, O’Brien and colleagues (72) examined the relative importance of skin vs core temperature for stimulating insulative acclimation. Subjects completed 5 weeks of daily 1 hour water- immersions (20^{o}C) while resting or performing exercise. Skin temperature decrements were similar during immersion for both groups. Rectal temperature fell by ~0.8^{o}C for the resting immersions group but was maintained in the exercise immersion group. Physiological responses during resting cold-air (5^{o}C) exposure were evaluated before and after the acclimation program. Neither group demonstrated insulative acclimation . However, the data suggested that core temperature reductions during acclimation sessions may be a needed stimulus for development of increased sympathetic responses to cold, while decreased skin temperature during acclimation sessions is sufficient stimulus for increased vasoconstrictor responses to cold. Finally they concluded that the duration (>60 min) of the core temperature reduction might be an important for inducing insulative acclimation.

Determinants of the Pattern of Adjustments. Figure 2 provides a theoretical schematic depicting the development of different patterns of cold adjustments (104). Brief, intermittent cold exposures appear sufficient to induce habituation of shivering and vasoconstrictor responses to cold, even when only very limited areas of the body surface are exposed and whole body heat losses are probably negligible. More pronounced physiological adjustments are observed only when the repeated cold-exposure causes significant body heat loss. Insulative adjustments appear to develop when repeated cold exposures are too severe for body heat loss to be offset by increased metabolic heat production; that is, when cold causes deep body temperature to decline significantly. The possibility that an enhanced thermogenic capability can develop in humans in response to chronic cold cannot be dismissed. It is tempting to speculate that the stimulus for this metabolic pattern of cold adaptation is prolonged periods in which significant body heat loss was experienced, but under conditions in which body heat production increased sufficiently to prevent a significant decline in deep body temperature. This speculation is not unjustified, since the metabolic pattern of cold adjustments has only been reported in studies in which acclimatization or acclimation was induced by exposure to such conditions, i.e. prolonged exposure to moderately cold air.

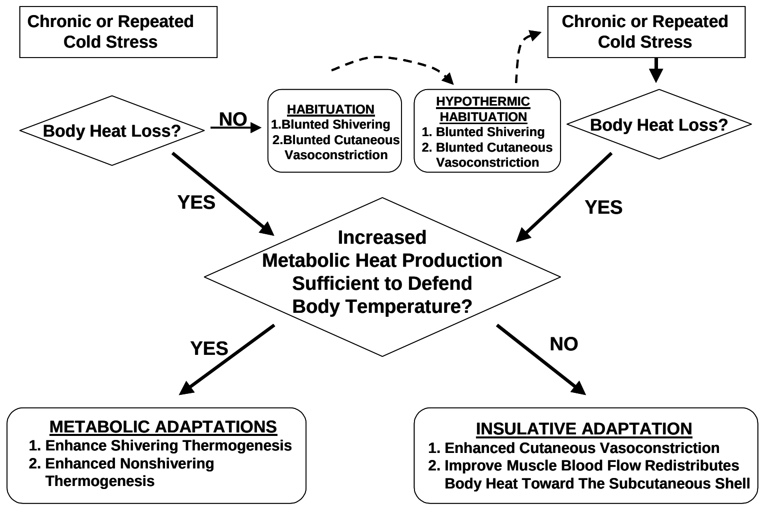

Figure 2. Flowchart illustrating a theoretical scheme to explain the development of different patterns of cold acclimatization / acclimation observed in humans (104).

Aternative explanations for the different patterns of cold adaptations have been proposed. Bittel (8) speculated that body composition and physical fitness determined the acclimation type. His data suggested that lean, fit individuals develop metabolic adjustments and fat, less fit individuals develop insulative adjustments. However, he studied too few subjects to statistically substantiate this hypothesis (8). Skreslet and Aarefjord (94)studied three scuba divers during a standardized cold-water immersion test before and at two week intervals throughout a 45 day period of daily diving in 2-4^{o}C sea-water. Initially, all subjects responded to cold with an increase in metabolic heat production, which in two out of three was sufficient to prevent rectal temperature from falling. After two weeks of diving, all three divers exhibited shivering habituation, and the two divers who tolerated the first immersion without a decline in rectal temperature now experienced a decline. After 45 days of diving, the subjects tended to maintain higher rectal temperatures and lower torso and thigh skin temperatures during immersion than during the initial test. Skreslet and Aarefjord (94) hypothesized that different cold adjustment patterns did not represent development of mutually exclusive physiological states, but rather, different stages in the progressive development of complete cold acclimatization. Thus, their divers initially responded to whole-body cold exposure by shivering; eventually, however, this response disappeared and insulative adaptations developed to help limit body heat loss.

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Maintaining Finger Dexterity in the Cold: A Comparison of Passive, Direct and Indirect Hand Heating Methods

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Summary

Examined finger dexterity performance and extremity comfort during cold exposure while an attempt was made to prevent or minimize hand cooling by either passive hand insulation (thin, knitted gloves and Arctic mitts), direct hand heating (electrically heated gloves), or indirect hand heating (heating the torso in an attempt to increase blood flow to the hands) with and without gloves. Eight male subjects were exposed to -25°C air (wind ~ 2 km/h) for three hours. A three-layer, Arctic clothing ensemble was worn during all experiments. Finger temperature, finger blood flow, toe temperature, rectal temperature, and finger dexterity were measured. Indirect hand heating was found to be superior to passive and direct hand heating because not only was finger comfort and finger dexterity maintained, but the whole body (toes included) remained comfortable for the full three-hour session. In addition, with indirect hand heating, fine finger dexterity tasks can be performed barehanded, if necessary, without the risk of cold injury.

Introduction

There is a military need for a hand heating system that will keep the hands warm and still allow for good finger dexterity. Soldiers will often remove their mitts to improve finger dexterity and will work with thin contact gloves to do a task more effectively. However, removing the bulky mitts or gloves can lead to finger discomfort or pain due to the decreased insulation over the hands. Frostbite is also a possibility, depending on the ambient condition and the length of the cold exposure. Therefore, removing bulky gloves or mitts to perform a task with thin contact gloves is not an ideal solution.

There are also some situations in which soldiers may remove their bulky gloves or mitts and their thin contact gloves in order to perform fine finger dexterity work with their bare hands. For example, a medic out in the battlefield may work barehanded to treat a soldier's wound. However, by working barehanded the medic is at a greater risk of cold injury. Therefore, it would be nice to have a hand heating system that could keep the hands warm even when there is minimal or no insulation over the hands!

It is especially difficult to keep the hands of soldiers warm and comfortable when they are inactive and are not generating very much metabolic heat. The extremities are the first to cool during periods of inactivity. A sniper, for example, may have to spend a prolonged period of time outdoors in the cold with little or no body movement while focusing on a target. It is important that the soldier remain focused on the target and not be distracted by the finger pain or discomfort that might occur while outside on a cold day. In addition, the sniper's shooting accuracy may be decreased if his core temperature decreases enough to cause shivering to occur. The involuntary muscle contractions that occur during shivering are definitely undesirable when the sniper is trying to hold his rifle steady. Therefore, it would be ideal to keep the body and fingers comfortable in order to maximize shooting performance.

Purpose

To examine finger dexterity performance and extremity comfort during cold exposure while an attempt was made to prevent or minimize hand cooling by either passive hand insulation (thin, knitted gloves and Arctic mitts), direct hand heating (electrically heated gloves), or indirect hand heating (heating the torso in an attempt to increase blood flow to the hands).

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Methods

Subjects

Eight healthy, non-smoking male volunteers with the following characteristics were recruited (mean±S.D.): age 32.8±7.4 years, height 176.4±6.3 cm, weight 82.4±7.5 kg, and body surface area 1.99±0.11 m^2. Body surface area was calculated using the formula of Dubois and Dubois (5). All subjects were medically screened by a physician at DCIEM before being asked for their written consent. This study was approved by the Human Ethics Committee at the Defence and Civil Institute of Environmental Medicine (DCIEM).

Ambient Condition and Clothing Worn

Subjects sat in a chair while exposed to an ambient temperature of -25°C (wind ~ 2 km/h) for three hours during all tests except when finger skin temperature (T_{fing}) reached 6°C, at which point the exposure was terminated. A three-layer, Arctic clothing ensemble [0.556 $m \cdot k^2/W$ (3.6 Clo)] was worn during all experiments. The three-layer system included a fleece garment (first layer), an uninsulated inner parka and pants (second layer), and an insulated outer parka and pants (third layer). A thin pair of long, cotton underwear was worn under the fleece pants. Standard CF mukluks, woolen socks, and a balaclava were also worn. The 3.6 Clo Arctic clothing insulation values did not take into account the long, cotton underwear worn under the fleece pants that have a Clo value of 0.3 (0.05 $m^2 \cdot °K \cdot W^{-1}$).

Hand Heating Conditions

Subjects were exposed to 4 conditions designated as passive, direct, indirect-passive, and indirect-bare. Each cold exposure was initiated at approximately 10 a.m. each morning. During the passive condition, thin, knitted gloves and Arctic mitts covered the hands. During the direct condition, the hands were actively heated with thin, electrically heated gloves and Arctic mitts were worn over the gloves. Finally, during the two indirect conditions, an electrically heated vest was used to actively heat the body in an attempt to increase the vasodilative response in the hands. During indirect-passive, the hands were insulated with thin, knitted, non-heated gloves and Arctic mitts, whereas during indirect-bare, the hands were bare during the entire 3 hour cold exposure. The tests were done one week apart over a time period spanning from January to July. The extremity temperature responses observed during this study are representative of a mixed, male population in which some subjects may have had a greater degree of peripheral cold acclimatization as a result of spending more time working or playing outdoors during the winter.

Design of Electrically Heated Vest and Gloves

The electrically heated vest consisted of 10 Kapton® insulated flexible heaters (Omega Engineering, Stamford, CT, USA) fixed around the torso as follows: two heaters (each 12 x 20 cm) on the chest, two heaters on the abdomen (each 8 x 30 cm), one heater at each side of the torso (each 8 x 20 cm), two heaters over the shoulder area (each 8 x 30 cm), and two heaters on the back (each 15 x 30 cm). The heaters covered a total area of 0.266 m^2. The heaters were not in direct contact with the skin, but inside a fire resistant pocket made of Nomex® fabric. In addition, a one centimeter layer of Thinsulate® insulation was placed inside the pocket on the outer surface of the heater. The Thinsulate® insulation was covered by a piece of reflective mylar to help reflect the radiative heat back to the torso. Once the heaters were placed inside the pockets, the pockets were sewn together to form a vest that covered a total area of 0.366 m^2. A tight, short-sleeved lycra body suit, which extended down to the mid-thigh level, was worn over the heaters to optimize the contact between the skin and the heaters. The electrically heated gloves used were constructed using a 300 strand tinsel wire that was knitted into a tight-fitting, nylon glove (Rapier Missile Glove, Vacuum Reflex Ltd., Suffolk, UK). The heating wire of each glove surrounded each finger and partially covered the back of the hand. The palms were not heated.

In regard to the electrically heated vest, pre-selected voltages were sent by five current-limiting power supplies (two model 6030A, 0-200V/0-17A, 1000W; three model 6034A, 0-60V/0-10A, 200W; Hewlett Packard) to the five pairs of heaters to achieve a skin temperature of 42±0.5°C under each heater. The power supplies were controlled by a computer that allowed the user to input the desired voltage for each pair of heaters. To ensure that the skin temperature under the heaters did not reach 45°C at any time, the computer turned off the heater completely if skin temperature reached 44°C. The electrically heated glove heater power was adjusted manually so that the mean finger skin temperature (T_{fing}) was the same as the T_{fing} established during the indirect-passive hand heating condition.

Finger Dexterity Tests

During the three-hour cold exposure, the subjects were asked to perform either a C-7 rifle disassembly and assembly task (C-7 rifle task) or a Purdue Pegboard test (PP test) every 30 min. The C-7 rifle task was done at time 0, 60, 120, and 180 min, whereas the PP test was done at time 30, 90, and 150 min. The C-7 rifle task was chosen because it was representative of the type of finger dexterity task that might be carried out by soldiers in the field. Subjects were required to do a "detailed stripping" of the rifle as outlined in "The Warrior" Canadian Forces combat survival manual (1). This involves an eight-step "field strip" (step nine was omitted for this experiment) and a six-step "detailed strip" (step three was omitted for this experiment). A total of 10 pieces (primarily made from metal) were disassembled. The process was then repeated in the reverse order to reassemble the C-7 rifle.

The PP test, on the other hand, is an extensively used fine finger dexterity test, which has been shown to be a reliable and valid measure of finger dexterity over the years (2, 9). The Purdue Pegboard consists of a pegboard with two columns of small holes down the middle of the board and four small cups along the top of the board that contain small metal pins, washers, and collars. The object of the PP test is to put together as many assembled units as possible in a one min period (one assembled unit consists of: pin, washer, collar, washer). The subjects were asked to perform three trials of the one-min test with approximately a 15-30 second break between each trial. A PP score was recorded for each trial. In calculating the PP score, the subject was awarded one point for each piece (i.e., pin, washer, or collar) placed on the PP board. In Fig. 5, each data point represents the average of three trials. During condition indirect-bare, the tests were done barehanded, whereas during the other three conditions, the Arctic mitts were removed, but the knitted, contact gloves were kept on for the duration of the dexterity tests. During the completion of the three PP test trials, the hands were exposed to the -25°C air for approximately four min, whereas the C-7 rifle task took approximately one-to-three min to complete.

The subjects were taught how to do the C-7 test and the PP test by the investigators during a 45 min training session which was arranged with the subject prior to start of the experimental sessions. In addition to the training session, during the experimental sessions, the subjects were asked to practice the C-7 and PP tests prior to each entry into the cold chamber. The subjects practiced the tests until a plateau in performance was observed. The subjects practiced the tests outside the cold chamber while wearing the same upper body CF Arctic clothing worn inside the cold chamber, but they were exposed to a 25°C ambient environment. Only shorts covered the lower body during the practice session.

Physiological Variables Measured

During the three-hour cold exposure, the following physiological variables were measured:

Finger skin temperature (T_{fing}) was measured using a cylinder-shaped thermistor (1.9 mm x 8.6 mm; Baxter 400 Series rectal/esophageal probe without the protective sheath covering (time constant = 0.9 seconds in well-stirred water), Baxter Healthcare Corp., Deerfield, IL, USA). A probe was placed on the pad of the "ring" fingertip of each hand. It was held in position on the skin with double-sided adhesive tape (3M Double-Stick Discs, 3M Medical Division, St. Paul, MN, USA) and a thin strip of surgical tape (3M Transpore Tape, 3M Canada Inc., London, ON, Canada) without constricting the finger.

Toe skin temperature (T_{toe}) was measured using a DCIEM lab-made, banjo probe (diameter = 10.2 mm, max height = 4.7 mm) that contains a protruding YSI 44004 thermistor bead. The probe is similar in shape to the YSI 081 standard surface probe (Yellow Springs Instruments, Yellow Springs, OH, USA), but it has a plexi-glass contact surface (instead of the stainless steel surface used in the YSI probe) and it has a time constant of 5 seconds in well-stirred water. A probe was placed on the medial side of the big toe of each foot. The toe thermistor was held in place against the skin with surgical tape (3M Transpore Tape, 3M Canada Inc., London, ON, Canada).

Rectal temperature (T_{re}) was measured via a thermistor (Pharmaseal 400 series, Baxter, Valencia, CA, USA) inserted 15 cm beyond the anal sphincter.

Measurements of T_{fing}, T_{toe}, and T_{re} were made five times per min over the course of three hours using a data acquisition system (model 3497A data acquisition/control unit; Hewlett Packard). An average value was printed out each min.

Finger blood flow (Q_{fing}) was measured using a 780 nm laser Doppler flowmeter probe (PF4001 Laser Doppler Flowmeter, Perimed, Stokholm, Sweden). A blood flow probe was placed next to each finger temperature thermistor. The unit of measurement used to represent the skin blood flow is the perfusion unit (PU). This is a relative unit of blood flow. A calibration standard is used to adjust the laser Doppler flowmeter readings to coincide with the readings obtained with a motility standard. Q_{fing} was measured 15 times per minute for three hours and an average Q_{fing} was taken every minute.

Statistical Analyses

A two-way ANOVA for repeated measures was used to compare conditions indirect-passive, direct and passive. The independent variables were "heating method" and "time". A two-way ANOVA was also used to compare the indirect-passive and indirect-bare conditions. The independent variables were "hand insulation" and "time". These analyses were done for the dependent variables C-7 rifle time, PP score, T_{fing}, T_{toe}, and T_{re} from 0 to 180 min. Five-min averages were calculated for the 180 min of data so that time 2, 7, 12 min, etc. represented the data from 0 to 4 min, 5 to 9 min, 10 to 14 min, etc. Five-min averages were not calculated for the finger dexterity data (i.e., C-7 rifle time and PP score) because data for these variables were collected every 30 to 60 min. Results were considered statistically significant at $p \leq 0.05$ (using the Greenhouse-Geisser adjustment for repeated measures). A Newman Keuls post-hoc test was used to determine if there was a significant difference in any of the dependent variables from 0 to 180 min. All values are presented as mean±SE.

Results

Finger skin temperature (Fig. 1)

T_{fing} was maintained at an average of 35±0.1°C for three hours during the indirect-passive and direct hand heating conditions, whereas during the indirect-bare hand heating condition, T_{fing} cycled between 24±1.3°C and 33±0.9°C for three hours. The hands were very comfortable. During the passive heating condition, T_{fing} decreased from 35±0.3°C to 12±0.5°C from the beginning to the end of the exposure and remained below 15°C for the last 90 min of the cold exposure. This was very uncomfortable for most subjects.

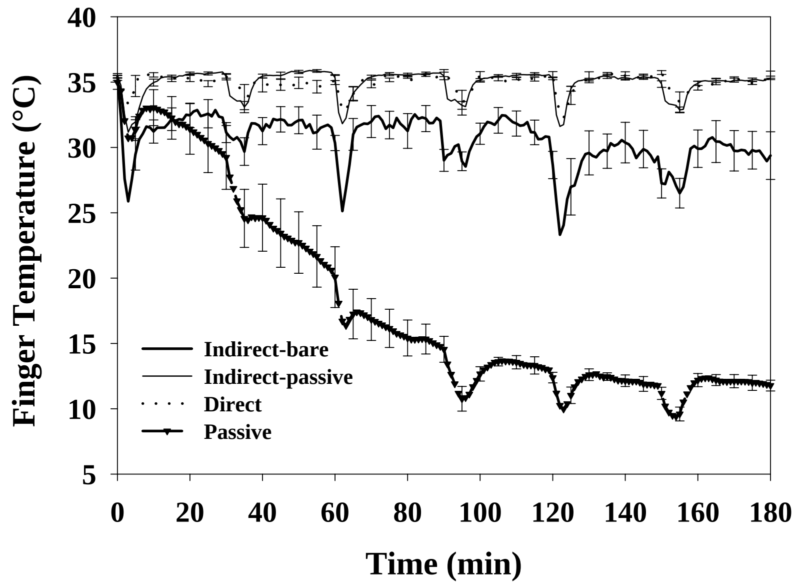

Fig. 1 *Mean finger skin temperature as a function of type of heating over time during exposure to -25°C air. Mean±SE (n=8).*

Finger blood flow (Fig. 2)

Q_{fing} was maintained at 223±28 PU and 255±19 PU during the indirect-bare and indirect-passive hand heating conditions, respectively, whereas during direct hand heating, Q_{fing} decreased from 213±21 PU to 27±5 PU from time 10 to 180 min. During passive heating, Q_{fing} decreased from 191±50 PU to 25±5 PU from time 10 to 180 min. Notice that during the direct hand heating method, blood flow was very low relative to the indirect heating-passive insulation condition, even though finger temperature was maintained, on average, at 35±0.1°C in both conditions. Hence, this shows that electrically heated gloves only heat the surface of the hand. During the dexterity tests, the Q_{fing} data was not presented due to movement artefacts.

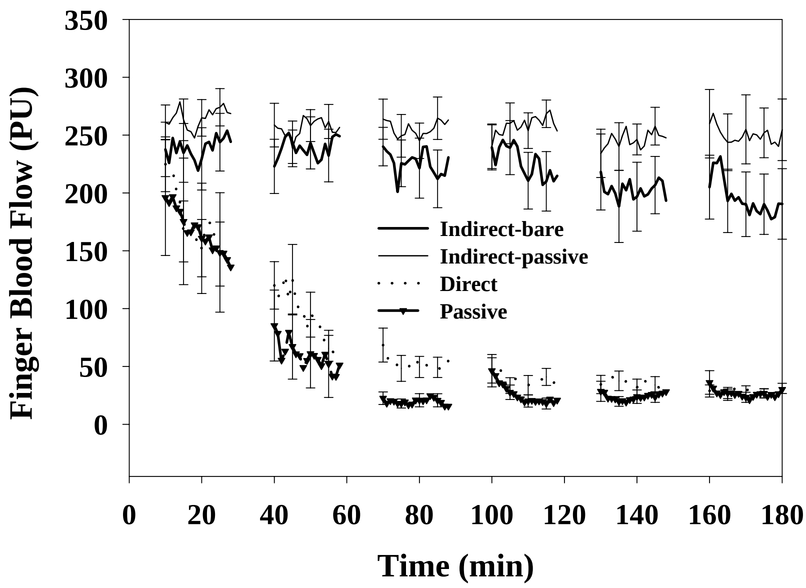

Fig. 2 *Mean finger blood flow as a function of type of heating over time during exposure to -25°C air. Mean±SE (n=8).*

Toe skin temperature (Fig. 3)

T_{toe} was maintained at 33±0.2°C during the indirect-passive heating condition, whereas during the indirect-bare condition, T_{toe} decreased from 33±1.0°C to 28±1.9°C over the course of three hours. During the passive and direct conditions, T_{toe} decreased from 33±1.0°C to 9±0.3°C from the start to the end of the exposure. T_{toe} was ≤ 15°C during the last 90 min of the cold exposure.

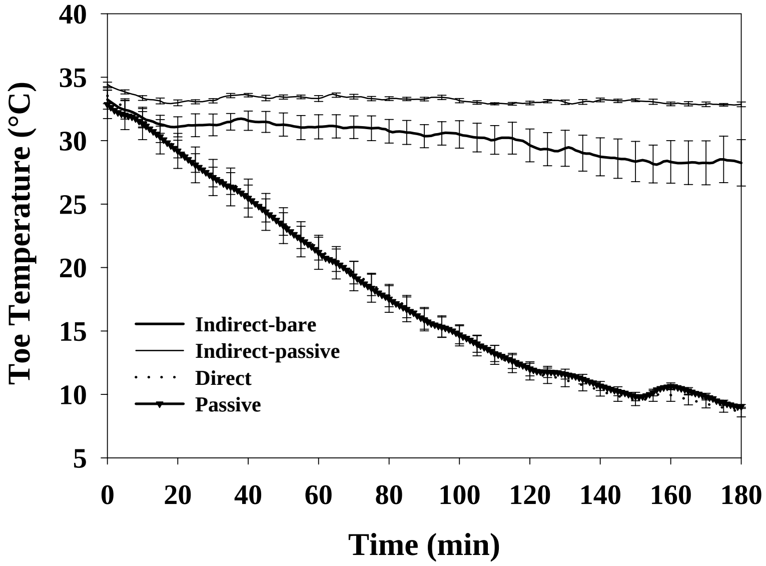

Fig. 3 *Mean toe temperature as a function of type of heating over time during exposure to -25°C air. Mean±SE (n=8). Direct condition plot is directly below passive condition plot.*

Δ Rectal temperature (Fig. 4)

During the indirect-passive heating condition, T_{re} increased by 0.23±0.04°C after an hour, relative to the start of the experiment, and then slowly decreased back down to its original value (at time 0 min) by time 180 min. There was no significant change in T_{re} during the indirect-bare condition. During the direct and passive conditions, T_{re} decreased significantly by 0.64±0.06°C and 0.57±0.08°C, respectively, by time 180 min.

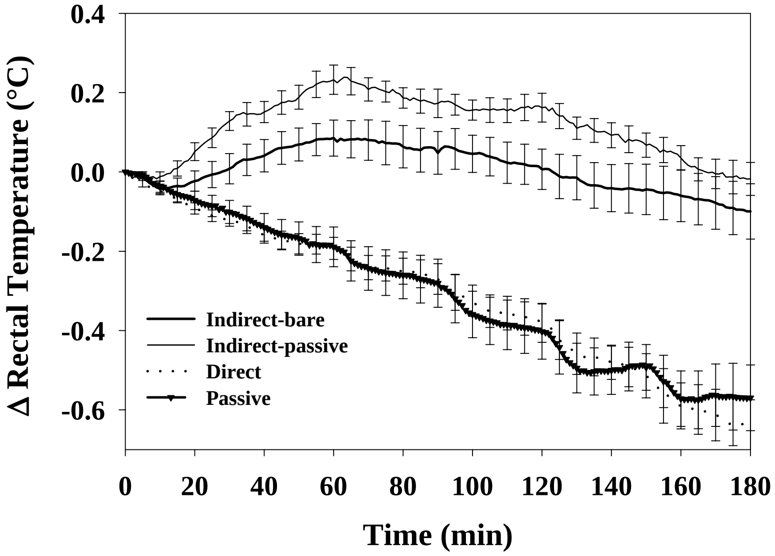

Fig. 4 *Mean change in rectal temperature as a function of type of heating over time during exposure to -25°C air. Mean±SE (n=8).*

Finger dexterity performance

Purdue Pegboard Score (Fig. 5) and C-7 Rifle Test Time (Fig. 6)

During the Purdue Pegboard finger dexterity tests, the passive hand heating condition was the only condition in which there was a significant decrement in finger dexterity over time (40% decrease after 150 min, relative to performance at time 30 min). At time 150 min, the Purdue Pegboard (PP) score was not significantly different between conditions indirect-passive and direct. During the indirect-passive and direct hand heating conditions, PP score remained stable from time 30 to 150 min at 20±2 and 18±2 points, respectively, whereas during the passive condition, PP score decreased significantly from 18±3 points at time 30 min to 11±1 points by time 150 min. During indirect-bare, PP score remained relatively stable at 48±3 points. Finger dexterity improved by 60% when the hands were bare compared to wearing gloves (i.e., compare PP scores between indirect-passive and indirect-bare). This is in agreement with Havenith and Vrijkotte's (6) finding that finger dexterity decreases by up to 70% when gloves were worn compared to bare-hand performance.

During the C-7 rifle finger dexterity tests, the passive hand heating condition, once again, was the only condition in which there was a significant decrement in finger dexterity over time (30% decrease after 180 min, relative to performance at time 0 min). It should be noted that, unlike the Purdue Pegboard test, there is an inverse relationship between finger dexterity and the rifle test time. That is, a higher rifle time corresponds to a poorer dexterity performance because it takes the subject a longer period of time to disassemble and reassemble the rifle. At time 180 min, the C-7 rifle test time was not significantly different between conditions indirect-passive and direct. During the indirect-passive and direct hand heating conditions, C-7 rifle test time remained stable at 96±5 and 98±6 sec, respectively, whereas during the passive condition, C-7 rifle test time increased significantly from 104±6 sec at time 0 min to 144±19 sec by time 180 min. During indirect-bare, C-7 rifle time remained relatively stable at 90±5 sec. Finger dexterity was not improved when the hands were bare compared to wearing gloves (i.e., compare C-7 rifle test scores between indirect-passive and indirect-bare) most likely because the C-7 rifle test is a test of gross finger/hand dexterity as opposed to a test of fine finger dexterity (i.e., the Purdue Pegboard test).

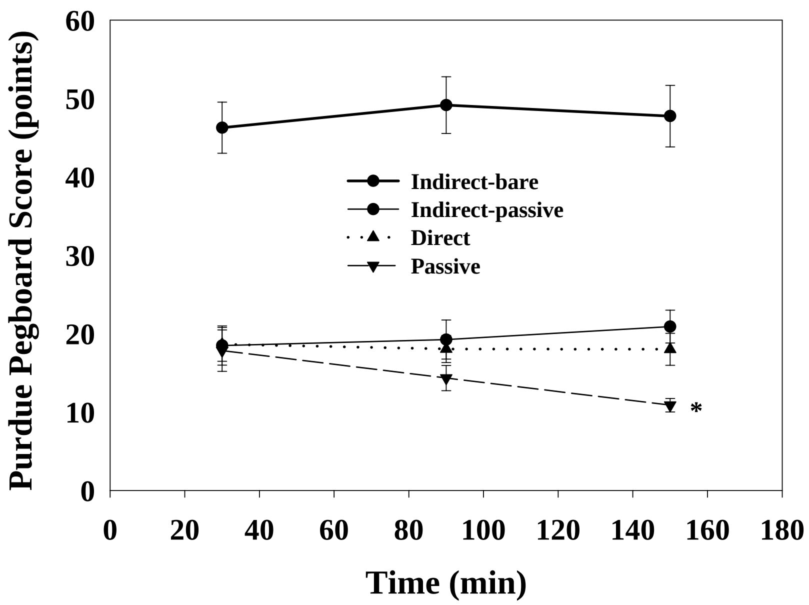

Fig. 5 *Mean Purdue Pegboard (PP) score as a function of type of heating over time during exposure to -25°C air. Mean±SE (n=8). * significant difference in PP score during passive hand heating condition at time 150 min relative to PP score during direct hand heating condition at time 150 min.*

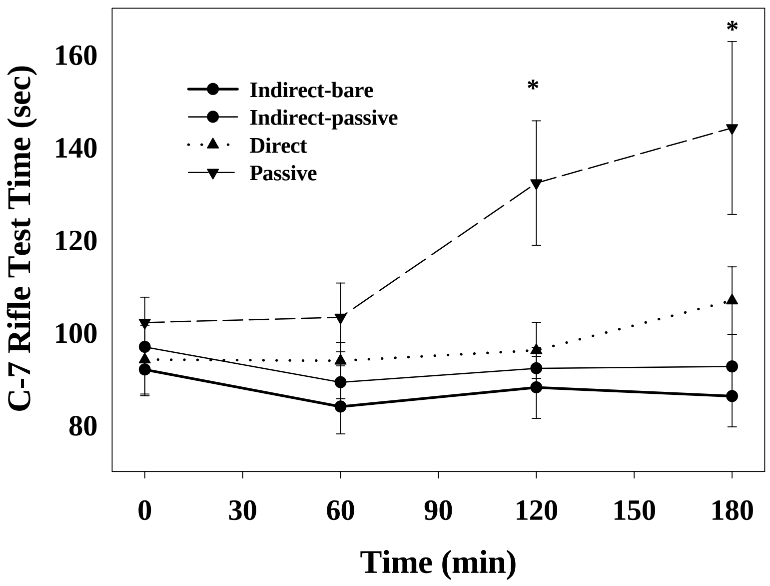

Fig. 6 *Mean C-7 Rifle Test time as a function of type of heating over time during exposure to -25°C air. Mean±SE (n=8). * significant difference in C-7 rifle test time during passive hand heating condition at time 120 and 180 min relative to C-7 rifle test time during direct hand heating condition at time 120 and 180 min.*

Discussion

Indirect hand heating (torso heating) has many advantages over passive (gloves and Arctic mitts) and direct (electrically heated gloves) hand heating. Most notably, the ability to maintain extremity comfort, finger dexterity, and body comfort (no shivering observed) in the cold (-25°C) while only wearing thin, contact gloves. In addition, with indirect hand heating, finger and toe temperatures remain comfortable (>25°C) without the use of any direct auxiliary hand/foot heating devices which are prone to wear and tear during repetitive work in the cold. Another problem with electrically heated insoles/socks is that the feet may be comfortable when an individual sits in the cold, but the feet may be too hot when pressure is applied to the sole of the foot by standing (7). Finally, indirect hand heating can maintain finger dexterity and finger comfort even when the hands are bare. This allows a soldier to perform fine finger dexterity work, while minimizing/eliminating the risk of frostbite.

In the present study, direct hand heating was effective in maintaining finger dexterity for three hours during exposure to -25°C air, even though finger blood flow was minimal. This seems to suggest that finger dexterity can be maintained as long as finger skin temperature is relatively high, regardless of finger blood flow; however, such a conclusion cannot be made without considering the effect of forearm muscle temperature on finger dexterity. LeBlanc (8) found that a cool forearm (muscle temperature not reported) can significantly decrease finger dexterity (due to the effect of muscle cooling on finger movement) even if the hand is immersed in 33°C water. Finger dexterity will most likely decrease, regardless of a high finger skin temperature, once forearm muscle temperature falls below a certain temperature threshold. A recent study found that finger dexterity was not affected (when finger skin temperature was maintained above 30°C) even if the forearm muscle temperature was decreased to 30°C (3). Therefore, the forearm temperature threshold for a decrease in finger dexterity to be observed is below 30°C.

Hence, due to the effect of forearm cooling on finger dexterity, a decrement in finger dexterity may have been observed with direct hand heating if less clothing insulation was worn. In addition, the earlier, and possibly greater intensity of shivering observed with less insulation may have directly affected finger dexterity performance due to the involuntary muscle movements that would affect hand/finger steadiness. A previous study (done at the same ambient temperature as the present study) found that whole-body

shivering occurred during the last two hours of a three-hour session when 2.6 Clo was worn over the body (4). Indirect hand heating may be more effective in maintaining finger dexterity (relative to direct hand heating) when the body clothing insulation is reduced somewhat compared to the insulation worn during the present study. Further research is needed to answer some of these proposed hypotheses.

Conclusion: Indirect hand heating is superior to passive and direct hand heating if it is necessary to do fine finger dexterity work in the cold for an extended period of time.

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Cooling of Hands and Fingers Wetted by Snow

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Summary

While working with bare hands in winter, hands and fingers get often contact with loose snow. The snow then attaches to the skin and melts quickly, which causes rapid cooling. However, the effect of snow cooling is not quantified. In this study the effect of ca. 2 s immersion of hand into pulverized snow on subsequent hand and finger temperatures at –10 °C and 2.0 m/s wind were studied. Non-immersed hand was used as a reference. After the snow immersion, the immersed and non-immersed hands were exposed to wind for 3 min. In the non-immersed hand, the skin temperatures in fingers decreased in 3 min to 12.4 - 15.2 °C and in hand to 19.4 - 22.7 °C. In the immersed hand, finger temperatures were 6.1 - 8.4 °C lower than in the non-immersed hand, measured 30 s after the immersion. At the end of the 3 min cold exposure, the temperatures in the different sites of the immersed hand were still 2.9 - 7.0 °C lower than without immersion. The results emphasise the marked cooling effect of single snow immersion on hand and especially on finger temperatures. Snow immersion markedly increases the risk of frostbite.

Introduction

Military tasks must often be performed with bare hands to be able to handle small objects. Complaints of cold pain or numbness have often been recorded. Our recent winter measurements show especially low finger temperatures while training with mortars, while rifle shooting, using keyboards of communication systems and handling metal dishes even at relatively high ambient temperatures (at -5 - 0 °C).

Exposing bare hands to cold increases radiative, conductive (contact cooling) and convective (wind chill) heat loss, and if the hands are wet, also evaporative heat loss. There are methods to predict finger cooling caused by convective (e.g., Oakley 1990) and conductive heat loss (e.g., Chen et al. 1996, Rintamäki and Rissanen 1997, Den Hartog et al. 2000). However, bare hands are often unintentionally in contact with snow, or even immersed in snow, which can increase heat loss at the same time due to contact cooling, due to the heat required for the thawing of snow, and due to increased evaporation. To our knowledge, there is no information about the effect of snow immersion on hand and finger temperatures.

The aim of this study was to quantify the effect of snow immersion on hand and finger temperatures.

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

Material and Methods

Four men, aged 34 - 47 years were exposed to cold. With ca. 2.5 clo clothing the thermoneutral subjects entered the wind tunnel (–10 °C and 2 m/s wind), removed mittens and immersed one hand into soft pulverized snow (natural snow, less than 24 h old) for ca. 2 seconds so that the hand up to the wrist was thoroughly in contact with snow. Immediately after the immersion, the hand was shaken briskly to remove melted and non-melted snow, but the hand was not dried otherwise. After that the test subjects stood for 3 min in the wind tunnel, fingertips towards the wind. Then the subjects moved to 21 °C, and the rewarming was recorded for 10 min. Skin temperatures of forefinger (palmar and dorsal sides, the first phalanx), little finger (palmar side, the first phalanx) and hand (palmar and dorsal sides) were recorded at 10 s intervals with YSI 409b thermistors and Squirrel 1200 datalogger. The test was repeated 3 days later with another hand immersed in snow.

Results

After the 3-min cold exposure, the skin temperatures without snow immersion were in little finger 13.2 ± 1.2 °C (mean ± SE, n = 8) (figure 1), in forefinger 15.2 ± 0.3 / 12.4 ± 1.0 °C (palmar/dorsal sides) and in hand 19.4 ± 0.7 / 22.7 ± 1.1 °C (palmar/dorsal sides). Snow immersion decreased all skin temperatures considerably: in comparison to dry hand, snow immersion decreased little finger temperature further by 8.4 ± 1.9 °C, forefinger by 8.0 ± 1.0 / 6.1 ± 1.0 °C and hand by 7.2 ± 1.1 / 7.0 ± 1.1 °C for 30 s after the immersion. At the end of the 3 min cold exposure, the effect of immersion was 7.0 ± 1.0 °C, 6.5 ± 0.7 / 4.7 ± 1.1 °C and 2.9 ± 0.4 / 4.4 ± 1.5 °C, respectively (figure 2). During the 3 min cold exposure after the immersion, the melted snow was evaporated almost totally and hand became almost dry.

After the cold exposure, little finger temperature was recovered first to the pre-exposure level (in 4 min at room temperature), and it even exceeded the pre-exposure level by ca. 1 °C. Forefinger reached the pre-exposure level in 7 min after the cold exposure. The temperatures in dorsal and palmar side of the hand remained ca. 2 °C below the pre-exposure level even 10 min after the cold exposure.

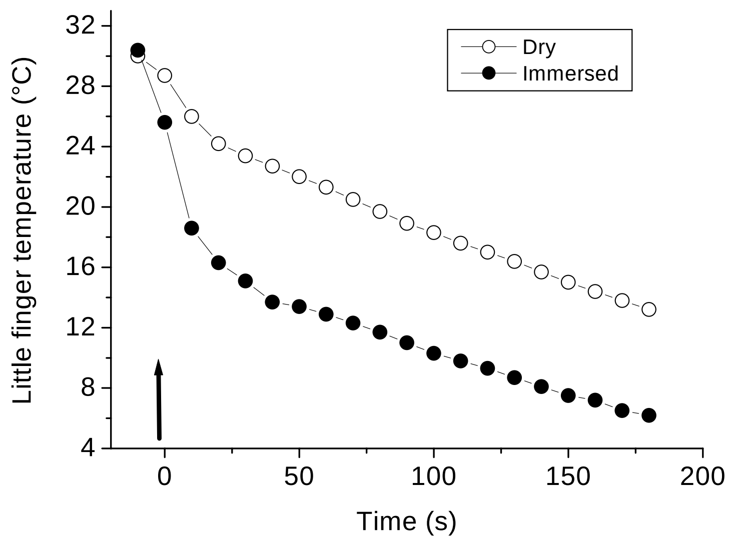

Figure 1. Little finger temperature, measured from the palmar side during cold exposure, with and without snow immersion. The arrow points the start of the ca. 2 s immersion.

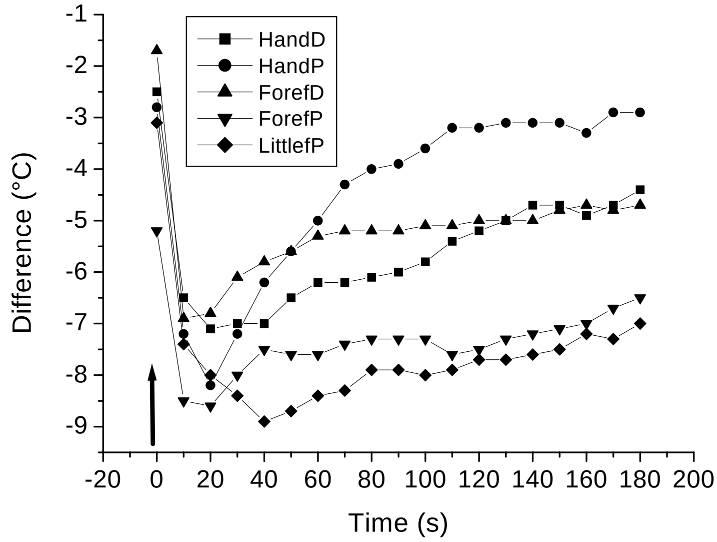

Figure 2. Temperature difference between dry and snow-immersed hand. The arrow points the start of the ca. 2 s immersion. HandD = dorsal side of the hand, HandP = palm, ForefD = dorsal side of forefinger, ForefP = palmar side of the forefinger, LittlefP = palmar side of the little finger.

Discussion

The present results emphasise the marked cooling effect of single snow immersion on hand and especially on finger temperatures. Because the cooling effect was most conspicuous almost immediately after the immersion, the heat loss due to the thawing of snow had obviously a marked role. Moreover, evaporation of the melted snow obviously increased the heat loss.

The ca. 8 °C additional decrease in finger skin temperatures by snow immersion points out how important it is to protect the hands during manual tasks in winter. Snow immersion markedly increases the risk of frostbite. If it is necessary to perform a task with bare hands, possibilities for quick rewarming of hands should be readily available. According to the prediction model of Oakley (1990), the freezing time of finger would be more than 8 min at –10 °C with 2m/s wind. Linear extrapolation of the present data suggests that the freezing time of a non-immersed little finger would be, on the average 7.7 min, and ca. 6.2 min when immersed into snow.

The increased finger skin temperatures observed during rewarming are obviously caused by cold-induced stimulation of finger circulation. If fingers are repeatedly exposed to cold, the increased circulation may protect from cooling to some extent.

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The Effects of Exhaustive Exercise on Thermoregulatory Fatigue During Cold Exposure

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Summary

Two experiments were conducted to examine whether acute (one-hour) or chronic exertional fatigue (3-7 days) would impair the thermoregulatory response during subsequent cold exposure thereby leading to an accentuated core temperature reduction compared to when the same individual was exposed to cold in a rested condition. In Study 1, ten men rested for 2 hours during a standardized cold air test (CAT, 4.6°C) following 2 treatments: 1) 60 min of cycle exercise (EX) at 55% $VO_{2\ peak}$ and 2) passive heating (HEAT). EX was performed during a 35°C water immersion (WI) and HEAT was conducted during a 38.2°C WI. The duration of HEAT was individually adjusted (mean = 53 min) so that rectal temperature (T_{re}) was similar at the end of WI in both EX (38.2°C) and HEAT (38.1°C). During CAT following EX, relative to HEAT: 1) T_{re} was lower ($P < 0.05$) from min 40-120, 2) mean weighted heat flow was higher ($P < 0.05$), 3) insulation was lower ($P < 0.05$), and 4) metabolic heat production was not different. In Study 2, thirteen men (10 experimental and 3 Control subjects) performed a cold-wet walk (CW) for up to 6-h (6 rest-work cycles, each cycle one h in duration) in 5°C air on three occasions. One cycle of CW consisted of 10 min standing in the rain ($5.4\ cm \cdot hr^{-1}$) followed by 45 min walking ($1.34\ m \cdot s^{-1}$, $5.4\ m \cdot s^{-1}$ wind). Clothing was saturated at the start of each walking period (0.75 clo vs. 1.1 clo when dry). The initial CW trial (Day 0, D0) was performed (afternoon) with subjects rested before initiating exercise-cold exposure. During the next 7 days, 4-h of exhaustive exercise (aerobic, anaerobic, resistive) was performed each morning. The subsequent two CW trials were performed on the afternoon of days 3 (D3) and 7 (D7), ~ 2.5-h after the cessation of fatiguing exercise. For the Control group, no exhaustive exercise was performed on any day. Thermoregulatory responses and body temperature during CW were not different on D0, D3, and D7 in the Control group. In the experimental group, mean skin temperature was higher ($P<0.05$) during CW on D7 and D3, than D0. Rectal temperature (T_{re}) was lower ($P<0.05$) and the ΔT_{re} was greater ($P<0.05$) during the 6th hour of CW on D3. Metabolic heat production during CW was similar among trials. These results suggest that prior physical exercise may predispose a person to greater heat loss and to experience a larger decline in core temperature when subsequently exposed to cold air. The combination of exercise intensity and duration studied in these experiments did not fatigue the shivering response to cold exposure.

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

Introduction

Exercise has been conjectured to increase an individual's risk of hypothermia during cold exposure (2, 15). However, experimental and clinical evidence for this is largely anecdotal. Over 30 years ago, Pugh (7, 8) concluded that exercise-induced fatigue was an etiologic factor predisposing hikers, climbers, and outdoorsman to hypothermia, but he provided no data demonstrating this belief with a physiological mechanism for this predisposition. Recently, Thompson and Hayward (12) suggested that exercise during cold-wet exposure may fatigue shivering thermogenesis, but their findings did not definitively support their speculation. Others (4, 16) have reported that exercise performed before subsequent cold water immersion exacerbates the fall in core temperature, but these results were inconclusive because pre-immersion core temperature differed between the experiments (4), or a cross-sectional methodology was employed (16). Furthermore, because water has such a high thermal conductivity, peripheral heat loss during cold water immersion may be too pronounced for exercise effects on thermal balance and thermoregulatory effector responses to be detected.

Exercise could increase the risk of hypothermia during subsequent cold exposure due to several reasons. First, exercise might mediate "thermoregulatory fatigue" which would blunt shivering responses and reduce vasoconstriction during subsequent cold exposure. For example, we (17) have observed that a prolonged period of physical exertion coupled with sleep deprivation and negative energy balance resulted in a lowered threshold for shivering despite normal plasma glucose concentrations. Those findings, however, did not allow isolation of the effects of previous exercise from sleep deprivation and negative energy balance. Second, cold exposure immediately after performing leg exercise might result in accentuated heat loss from "thermoregulatory lag". Thermoregulatory responses are aimed at facilitating heat dissipation during exercise in temperate conditions (10) and subsequent cold exposure might mediate a "lag" in switching from heat loss to conservation. Evidence for this might include increased heat loss from areas of active cutaneous vasodilation such as the torso and arms. Third, exercise might mediate greater heat loss during subsequent cold exposure due to "heat redistribution" to active limbs. During exercise, active skeletal muscle increases perfusion and perfusion can remain elevated for extended durations (11) facilitating regional heat loss over these active limbs during exercise (9). Evidence for a "heat redistribution" might include greater regional heat loss over the active limbs (legs) during subsequent cold exposure .

These studies examined whether exercise impairs the body's capability to maintain thermal balance during subsequent cold exposure. It was hypothesized that a greater decrease in core temperature (T_{core}) would occur during cold exposure following either acute (Study 1) or chronic (Study 2) exercise compared to cold exposure preceded by resting. We hypothesized that exercise would mediate some combination of "thermoregulatory fatigue", "thermoregulatory lag", and/or "heat redistribution" which would be manifested as a more rapid cooling rate during cold exposure.

Methods

Study 1

Subjects. Ten, healthy men volunteered to participate in this study as test subjects. Physical characteristics were age, 24.7 ± 1.7 (SE) yr; height, 176.8 ± 2.1 cm; mass, 78.1 ± 3.5 kg; body surface area, 1.93 ± 0.05 m^2; peak oxygen uptake (VO_{2peak}), 46.1 ± 1.3 $ml \cdot kg^{-1} \cdot min^{-1}$; percent body fat, 15.0 ± 1.2 %; and skinfold thickness, 3.2 ± 0.4 mm.

Preliminary testing. Body composition was measured using dual energy x-ray absorbitometry (Model DPX-L, Lunar Corp., Madison, WI). All subjects completed an incremental cycle ergometer test for determination of $VO_{2\ peak}$. Briefly, subjects pedaled at 70 watts for 2 min with the resistance increased by 35 watts every 2 minutes until the subject was exhausted and could no longer maintain the exercise intensity.

Experimental Design. Subjects completed two experimental trials, on separate days, spaced by one week. Subjects refrained from smoking, taking medication, and exercising 12 hours before any testing session. Each trial consisted of a standardized cold air test (CAT) preceded by one of two manipulations: A) exercise (EX), or B) passive heating (HEAT). The EX trial consisted of 60 min semi-recumbent cycle ergometer exercise (EX), immersed to shoulder level in a water immersion pool at 35.0 ± 0.1°C followed by

the CAT. The immersion pool holds ~ 36,000 liters and is controlled within 0.5°C by a temperature control system. Mean exercise intensity was 55.4 ± 2.3 % $VO_{2\ peak}$ for EX. The HEAT trial consisted of sitting in the immersion pool at 38.2 ± 0.0°C until rectal temperature rose to match that at the completion of EX followed by the CAT. This approach precluded using a randomized design and the HEAT trial always followed the EX trial. Immediately following EX or HEAT, subjects toweled off, changed into dry shorts and socks, and were taken to the anteroom of the cold chamber for baseline measurements. This took approximately 20 minutes. Five minutes of baseline data (body temperatures, HR, metabolic rate) were collected outside the cold air chamber (22.8 ± 0.8°C) while the subject sat quietly, and then they rose and walked into the cold air chamber (4.6 ± 0.1°C) and reclined for up to 120 min in a nylon mesh lounge chair. While reclining, the subjects sat quietly and were not allowed to employ behavioral thermoregulation. The trials were all conducted at the same time of day to control for the potential influence of circadian rhythmicity.

Measurements and Calculations. Rectal temperature (T_{re}) was measured by a thermistor inserted 10 cm past the anal sphincter. Integrated heat flow and skin temperature disks (Concept Enginnering, Old Saybrook, CT) were secured at 5 (in water) and 8 (CAT) sites (right side of the body). Mean weighted skin temperature ($\bar{T}_{sk}$) during water immersion was calculated as follows: $\bar{T}_{sk} = 0.28T_{subscapular} + 0.14T_{forearm} + 0.08T_{triceps} + 0.22T_{calf} + 0.28T_{lateral\ thigh}$. During CAT, $\bar{T}_{sk}$ (°C) was calculated as follows: $0.06T_{foot} + 0.17T_{calf} + 0.28T_{lateral\ thigh} + 0.14T_{chest} + 0.07T_{tricep} + 0.07T_{forearm} + 0.14T_{subscapular} + 0.07T_{hand}$. Mean weighted heat flow (HF, $W \cdot m^{-2}$) was calculated as follows: $0.06HF_{foot} + 0.17HF_{calf} + 0.28HF_{lateral\ thigh} + 0.14HF_{chest} + 0.07HF_{tricep} + 0.07HF_{forearm} + 0.14HF_{subscapular} + 0.07HF_{hand}$. Tissue insulation was calculated as follows: $I_T = (T_{re}-\bar{T}_{sk})/HF$ (10). Mean body temperature ($\bar{T}_b$) was calculated as follows: pre-CAT, $\bar{T}_b = 0.8T_{re} + 0.2\ \bar{T}_{sk}$, during CAT, $\bar{T}_b = 0.67T_{re} + 0.33\ \bar{T}_{sk}$ (26). Temperature and heat flow measurements were made continuously using an automated data acquisition system.

Oxygen uptake (VO_2) was measured using an automated metabolic measurement and analysis system (Model 2900, Sensormedics, Yorba Linda, CA) at minutes 0 (baseline) and 30 during the water immersion. During CAT, VO_2 was measured at minutes 0 (baseline), 15, 35, 55, 75, 95, and 115. Metabolic heat production (M, $W \cdot m^{-2}$) was estimated from the VO_2 and respiratory exchange ratio (RER) using the following equation: $M = (0.23[RER] + 0.77) \bullet (5.873)(V\ O_2) \bullet (60/A_D)$ where A_D is body surface area (m^2).

Blood was drawn from an indwelling venous catheter (antecubital) in the left arm before beginning the CAT (min 0) and at minutes 15, 30, 60, 90, and 120 during CAT. Catheter patency was maintained between blood draws by injecting heparinized saline into the catheter. Blood samples were analyzed to determine plasma glucose concentration using an auto analyzer (Model 2300, Yellow Springs Instrument, Inc.) to ensure that subjects maintained euglycemia. Plasma norepinephrine (NE) was determined by gas chromatography.

Statistical Analyses. Data were analyzed using a 2-way repeated measures analysis of variance. When significant F-ratios were calculated, paired comparisons were made post-hoc using Newman-Keuls tests. The slope and threshold of each individuals $\bar{T}_b$ vs. $\Delta \dot{M}$ relationship was determined by least squares linear regression. Paired t-tests were used to determine if differences in slope or intercept data existed between EX and HEAT for $\bar{T}_b$ vs. ΔM. Data are reported as means $\pm$ S.E. Significance was accepted at $p < 0.05$.

Study 2

Subjects. Thirteen subjects participated in this study which was approved by the appropriate Institutional Review Boards. The subjects volunteered after being fully informed of the requirements and risks associated with participating in the research. Ten subjects performed exhaustive exercise (EX group) between cold-wet exposures whereas three volunteers did not (Control group). Subject characteristics were age, 24 ± 1 yr; height, 177 ± 2 cm; weight, 82.8 ± 3.6 kg; % fat, 16.4 ± 1.9%; $\dot{V}O_{2peak}$, 56.0 ± 1.8 $ml \cdot kg^{-1} \cdot min^{-1}$; and body surface area 1.99 ± 0.05 m^2 for the EX group and age, 28 ± 4 yr; height, 170 ± 5 cm; weight, 80.5 ± 8.0 kg; % fat, 20.0 ± 2.0%; $\dot{V}O_{2peak}$, 53.6 ± 3.2 $ml \cdot kg^{-1} \cdot min^{-1}$; and body surface area 1.91 ± 0.10 m^2 for the Control group.

Preliminary testing. Body composition was measured using dual energy x-ray absorbitometry (Model DPX-L, Lunar Corp., Madison, WI). An incremental treadmill test was used for determination of peak oxygen uptake ($\dot{V}O_{2peak}$). Briefly, subjects ran at 9.7-11.3 $km \cdot hr^{-1}$ at a 0% grade for 1.5 min. Thereafter, the grade increased 2% every 1.5 minutes until the subject became exhausted. The one repetition maximum (1-RM) of the upright row, chest press, latissimus dorsi pull-down, and biceps curl was determined for members of the exhaustive exercise group but not the control group. Subjects completed a series of no more than 6, single repetitions as resistance was increased incrementally until the subject could no longer lift the weight correctly. Approximately one minute elapsed between successive 1-RM attempts.

Experimental design. The subjects' body composition, peak oxygen uptake ($\dot{V}O_{2peak}$), and muscle strength were assessed before beginning the experiment. The subjects then completed three experimental cold, wet walks (CW) from ~ 1330-2000 hours when they were well-rested before beginning the heavy exercise regimen (D0), and after 3 (D3) and 7 (D7) consecutive days of exhaustive exercise (EX group) or at the same between trial intervals for the Control group. The purpose of including the Control group was to assess the possibility that three, repeated exposures to cold completed over a one week period would induce habituation or acclimatization to cold, separate from effects of the exhaustive exercise, although their small sample number limits statistical inferences. The Control group refrained from exercising for 24 hours before each CW. On D3 and D7, ~ 2.5 hours (140-170 min) elapsed between the end of the last daily exercise session and the subsequent CW. The CW was modified from an experimental protocol described by Weller et al. (14). Briefly, CW consisted of 360-min intermittent treadmill walking (six cycles of 10-min standing rest in the rain, 45-min walking, 5-min for transition between rest and walking) in an environmental chamber with air temperature set at 5°C. During the rain, the subjects stood still for 10 min (except for the initial cycle of rain, during which they sat) and were wetted at a rate of 5.41 $cm \cdot hr^{-1}$ under a sprinkler designed to simulate rainfall. Following each rest/rain period, subjects walked at 1.34 $m \cdot s^{-1}$ (3 mph) at 0% grade on a motor-driven treadmill. Wind velocity was 1.1 $m \cdot s^{-1}$ (2.5 mph) during the 10-min rain and 5.4 $m \cdot s^{-1}$ (12 mph) while walking. The CW for each subject was terminated if the rectal temperature was < 35°C, or if the subject asked to stop.

Each subject consumed one US Army Meal-Ready-to-Eat (1260 ± 29 kcals) 1.5 hr before each CW. During the rest/rain portion of each cycle (not including the first cycle), 250 ml of a commercial carbohydrate drink (Gatorade®, Quaker Oats, Barrington, IL) was consumed to help subjects maintain normal plasma glucose concentrations throughout CW. Before beginning CW, baseline measurements of temperature, oxygen uptake and thermal sensation were obtained in an anteroom outside the environmental chamber (22°C) for 20-min. Volunteers were tested in groups of 3-4 people. Clothing for each subject consisted of a US Army Battle Dress Uniform (cotton shirt, cotton-nylon jacket, cotton-nylon pants, cotton-nylon hat with ear flaps, socks, gloves, leather boots; clo = ~1.1). Additionally, during the rain, the subjects wore a 100% nylon rain hat and nylon boot gaiters. The clo value, following the rain, for a completely wetted uniform was 0.75 clo.

The exhaustive exercise routine for days 1-7 consisted of the following activities each day: running & sprinting (hiking substituted on D3 & D7), weightlifting, ergometry, and an anaerobic power test. Subjects ran 4.8 km at their personal best and sprinted 800 m three consecutive times. Weightlifting consisted of one set of repetitions to exhaustion on four different resistance exercises (row, chest press, lat pull-down, biceps curl), each at 70% of the one repetition maximum. Aerobic exercise consisted of four consecutive 20 min sets of stair-stepping (Stepmill, Stairmaster Corp., Seattle, WA), rowing (Concept II, Concept II Inc., Morrisville, VT), treadmill walking (substituted for rowing on D3 and D7), upright cycling (Model HRT-2000A, Preference), and semi-recumbent cycling (Model HRT-2000R, Preference), all at ~ 65% $\dot{V}O_{2peak}$. This percentage was estimated from the VO_2-HR relationship derived during the determination of $\dot{V}O_{2peak}$. A 5-min rest was allowed between bouts. One 30-sec anaerobic test (Wingate test) was performed on a cycle ergometer (CardioO_2, Ergometrix Corp., Minneapolis, MN) and concluded each exhaustive exercise session. Subjects' pedaled as fast as they could for 30-sec with resistance set at 5.8 $J \cdot rev^{-1} \cdot kg^{-1}$. Hiking (substituted for running and sprinting on D3 and D7) consisted of a 9.7 km hike over varied terrain at ~6.4 $km \cdot hr^{-1}$, carrying a 9.1 kg backpack. Exhaustive exercise was performed from 0900-1300 h (D1, D2, D5, D6) or 0700-1100 h (D3, D4, D7). Subjects were provided a carbohydrate-electrolyte beverage to drink *ad libitum* during the exhaustive exercise regimen.

Measurements and calculations. Rectal temperature (T_{re}) was measured every minute using a thermistor inserted 10 cm past the anal sphincter. Skin temperature (T_{sk}) was measured using thermistor disk sensors (Concept Engineering, Old Saybrook, CT) attached on the skin surface at five sites (ventral aspect of forearm, tricep, subscapula, anterior thigh, and calf). Mean weighted skin temperature ($\bar{T}_{sk}$) was calculated as: $\bar{T}_{sk} = 0.28T_{subscapular} + 0.14T_{forearm} + 0.08T_{triceps} + 0.22T_{calf} + 0.28T_{thigh}$. Heart rate (HR) was measured near the end of each walking portion of the CW from three chest electrodes (CM-5 configuration) and radiotelemetered to an oscilloscope-cardiotachometer (Hewlett-Packard). Oxygen uptake ($\dot{V}O_2$), carbon dioxide output, and minute ventilation were measured by open-circuit spirometry before CW (sitting) and during the 25-27th min of walking during each exercise portion of the rest-walking cycle. Additionally, in four subjects from the EX group and the three Control group subjects, expired air was collected immediately following the rain portion of each cycle to evaluate shivering thermogenesis during rest. Percent oxygen (Applied Electrochemistry S-3A), carbon dioxide (Beckman LB-2), and volume (Tissot Spirometer, Collins) were measured from a 1.5-min collection of the subjects' expired air into a Douglas Bag. Metabolic heat production ($\dot{M}$, $W \cdot m^{-2}$) was estimated from the $\dot{V}O_2$ and respiratory exchange ratio (RER) using the following equation: $\dot{M} = (0.23[RER] + 0.77) \bullet (5.873)(\dot{V}O_2) \bullet (60/A_D)$ where A_D is body surface area (m^2). Whole body insulation (I) was calculated using the following equation: $I = (T_{re}-\bar{T}_{sk})/\dot{M}$. Self-reported dietary and sleep records were kept each day beginning the day before the first CW and continuing through day 7.

Blood samples for determination of serum glucose and plasma catecholamines were collected after the subject sat quietly for 20 min on D0, D3, and D7 at 0700-h, before CW (~1315-h, glucose only), and 20-min following CW (post-CW) from an indwelling cannula in an antecubital vein. Plasma and serum were separated using a refrigerated centrifuge. Serum glucose was measured on an auto-analyzer (Model 2300, Yellow Springs Instrument, Inc., Yellow Springs, OH). Plasma catecholamine concentrations were measured with mass spectroscopy-gas chromatography. Plasma volume changes were determined from hemoglobin and hematocrit measurements.

Statistical analyses. Data were analyzed using a 2-factor (time X experimental trial) repeated measures analysis of variance. When significant F-ratios were calculated, paired comparisons were made post-hoc using Fisher's least significant difference test. Because exposure duration varied for each subject among the 3 trials, statistical analysis was performed on complete data sets for all three trials. For the EX group, data from 10 subjects were analyzed from 0-180 min and data from 4 subjects were analyzed for 360 min. For the Control group, data from the 3 subjects were analyzed for 240 min. There were missing data points at various points due to difficulty drawing blood samples from subjects during cold exposure. Therefore, catecholamine data were analyzed with t-tests between D0 and D3 and between D0 and D7. Unless otherwise specified, the level of significance for differences reported is $P < 0.05$. Data are presented as mean ± S.E.

Results

Study 1

Water Immersion. All subjects completed 60 min of cycling during EX. The mean immersion time required during HEAT to match the T_{re} rise observed during EX was 53.4 ± 5.0 min. The mean T_{re} at the end of the immersion periods were 38.19 ± 0.14°C and 38.08 ± 0.10°C, during EX and HEAT, respectively ($P > 0.05$). The average VO_2 ($L \cdot min^{-1}$) during immersions were 1.97 ± 0.12 and 0.34 ± 0.02, for EX and HEAT, respectively ($P < 0.05$). For EX, this VO_2 corresponded to 55.4 ± 2.3% of the measured $VO_{2\ peak}$. Final heart rates ($beats \cdot min^{-1}$) during immersion were 149.3 ± 6.1 and 102.1 ± 3.1, for EX and HEAT, respectively ($P < 0.05$). Weight loss (kg) from sweat was 1.07 ± 0.15 and 1.06 ± 0.18 during EX and HEAT, respectively ($P > 0.05$).

Rectal temperature (CAT). During the transition from the immersion pool to the cold air chamber, T_{re} fell during HEAT. Therefore, T_{re} at min 0 was slightly, but significantly higher (0.14°C, $P < 0.05$) in EX vs. HEAT (Figure 1). By the 10th min of cold air exposure, differences between trials were no longer apparent. However, by the 40th min of CAT, T_{re} had fallen lower ($P < 0.05$) during EX compared to HEAT and the difference between trials grew larger as exposure continued to the 120th min. The cooling rate ($°C \cdot h^{-1}$) from min 10 to the end of the exposure was faster ($P < 0.05$) for EX (-0.64 ± 0.07) than HEAT (-0.57 ± 0.04).

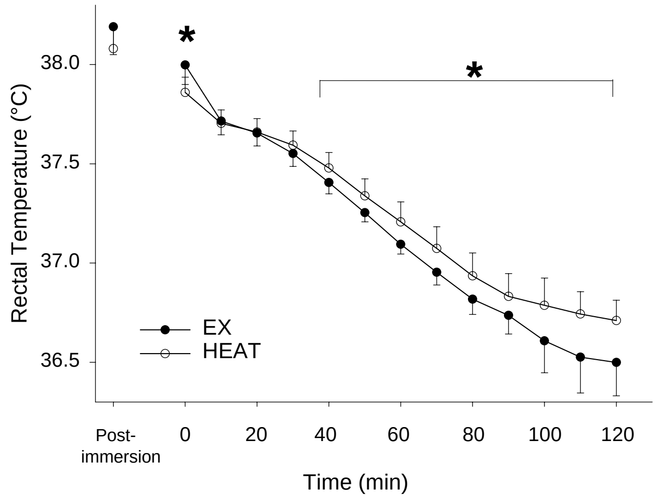

Figure 1. Rectal temperature vs. time for Exercise (●, EX) and Passive Heating (○, HEAT) experiments during cold air exposure. Values are mean ± SE. * Exercise significantly different than Control at specified times. Post-immersion denotes temperature at the end of the water immersion.

Heat flow (CAT). HF was higher ($P < 0.05$) during CAT in EX vs. HEAT (Figure 2). Also I_T during CAT was lower ($P < 0.05$) in EX compared to HEAT (Figure 2).

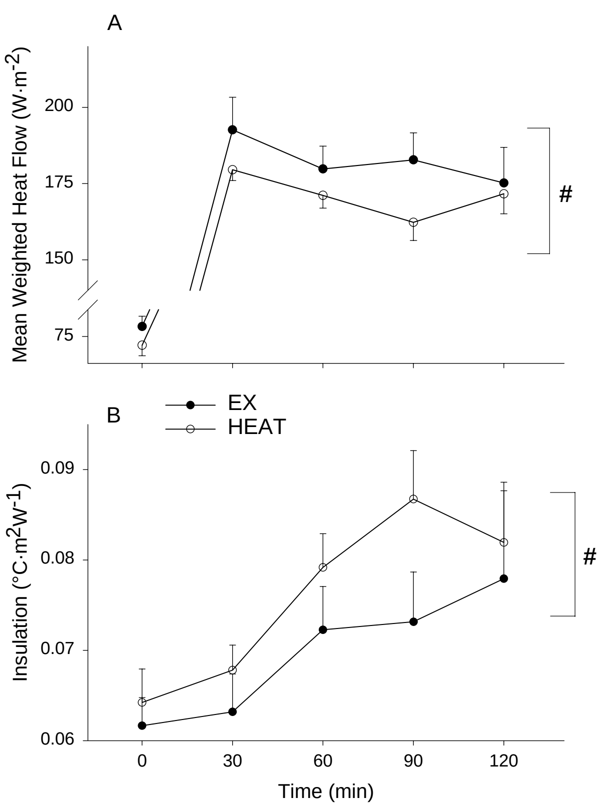

Figure 2. Mean weighted heat flow (A) and insulation (B) vs. time for Exercise (●, EX) and Passive Heating (○, HEAT) experiments during cold air exposure. Values are mean ± SE. #, main effect, Exercise significantly different than Control, P<0.05.

Individual site HF and I_T are presented in Figure 3. Calf HF and I_T demonstrated a significantly ($P < 0.05$) greater HF and lower I_T between EX and HEAT. Hand HF also tended ($p = 0.06$) to be higher in EX.

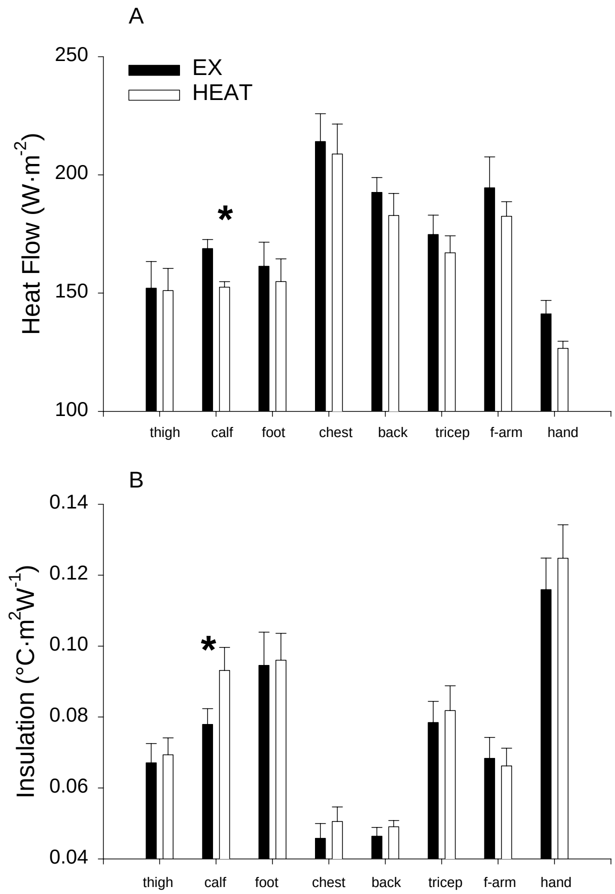

Figure 3. Individual heat flow (A) and insulation (B) for the 8 sites measured. Calf heat flow was higher (P < 0.05) and insulation lower (P < 0.05) during EX. Values are mean ± SE.

Metabolic heat production & heat debt (CAT). M did not differ between EX and HEAT at any time throughout CAT. The final M at min 115 was 146.6 ± 6.5 and 136.1 ± 3.6 $W{\cdot}m^{-2}$ for EX and HEAT, respectively. The relationships (slope and intercept) between mean body temperature ($\bar{T}_b$) and the corresponding increment in metabolic heat production over pre-CAT values (Δ M, a measure of shivering thermogenesis) did not differ between trials. Slopes ($W{\cdot}m^{-2}{\cdot}{°}C^{-1}$) were -33.8 ± 3.0 and -32.7 ± 3.4 for EX and HEAT, respectively. Intercepts (°C) were 34.5 ± 0.2 and 34.3 ± 0.1 for EX and HEAT, respectively.

Plasma glucose, norepinephrine (CAT). Plasma glucose concentrations were not affected by CAT in either trial and there were no differences between trials. Glucose values averaged between 4-6 $mmol{\cdot}L^{-1}$ throughout CAT. Plasma norepinephrine concentrations increased from 2.5 $nmol{\cdot}L^{-1}$ to 10-15 $nmol{\cdot}L^{-1}$ during cold air exposure, with no differences between EX and HEAT.

Study 2

Exercise Duration, Cold Tolerance, Food and Sleep Diaries.

Six subjects (4 in EX group; 2 in Control group) completed 360 min in all 3 cold exposure trials. The other 6 subjects in the EX group completed a minimum of 180 min in all three trials and the average time completed for the trials in these subjects was 305 ± 24, 281 ± 23, and 287 ± 25 minutes for D0, D3, and

D7, respectively. The third subject in the Control group completed 240 min in all three trials. One subject sustained a foot injury on Day 5 and did not participate in the Day 7 cold exposure. The main reasons for not completing all 6 hours during CW included hip flexor cramping and/or leg pain and overall body stiffness. Mean daily sleep reported ranged from 6.6-7.8 hours per night for the duration of the study. Mean body mass (kg), for all subjects, at the beginning of D0, D3, and D7, respectively, was 81.6 ± 3.2, 81.6 ± 3.2, and 81.3 ± 3.1. Mean daily caloric intake reported throughout the experiment was 2656 ± 94 $kcal \cdot day^{-1}$.

Temperature Regulation Responses (EX Group).

Rectal temperature. Rectal temperature was significantly higher during the first 2 hours (n = 10, F = 3.67, P < 0.001) and significantly lower in the 6th hour of cold exposure (n = 4, F = 2.02, P < 0.001) on D3 compared to D0 (Figure 4). T_{re} was also significantly higher in the 2nd and 3rd hours (n = 10) of cold exposure on D7, compared to D0, with no difference between these trials for the last three hours (n = 4) of exposure. The change in T_{re}, relative to the initial T_{re} at time 0 was significantly greater (F = 3.68, P < 0.001) during the 6th hour of cold exposure on D3 compared to D0.

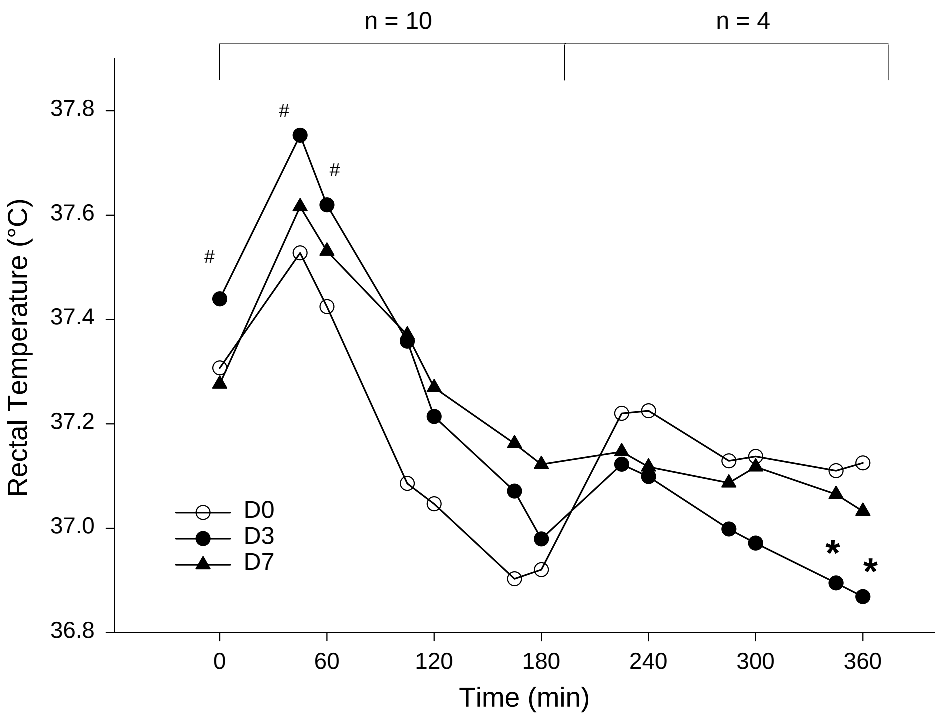

Figure. 4. Rectal temperature vs. time during cold exposure before (D0, ○), after 3 days (D3, ●) and after 7 days (D7, ▲) of physical exertion. Data from min 0 to min 180 are from 10 subjects and data from min 190 to min 360 are from 4 subjects. *, D3 significantly (P < 0.05) different than D0; ‡, D3 and D7 significantly (P < 0.05) different than D0; #, D3 significantly (P < 0.05) different than D0 and D7.

Skin temperature. Mean skin temperatures were significantly higher (F = 3.17, P < 0.001) on D7 and D3, vs. D0, from the 1st to 6th hour of cold exposure (Fig. 5). The change in mean skin temperature ($\Delta\overline{T}_{sk}$, a quantifier of the magnitude of vasoconstrictor response) was significantly less (F = 3.17, P < 0.001) in the 2nd and 3rd hours (n = 10) on D7, vs. D0 and D3. The $\Delta\overline{T}_{sk}$ for the 3rd through 6th hours was significantly less on both D7 and D3, compared to D0. Forearm skin temperature changes during the first 3 hours of cold exposure demonstrated a significantly smaller fall (F = 1.63, P < 0.05) in forearm skin temperature on D3 and D7, vs. D0, and the fall in calf skin temperature during the same time period was also significantly less (F = 2.35, P < 0.001) on D7, vs. D0 and D3.

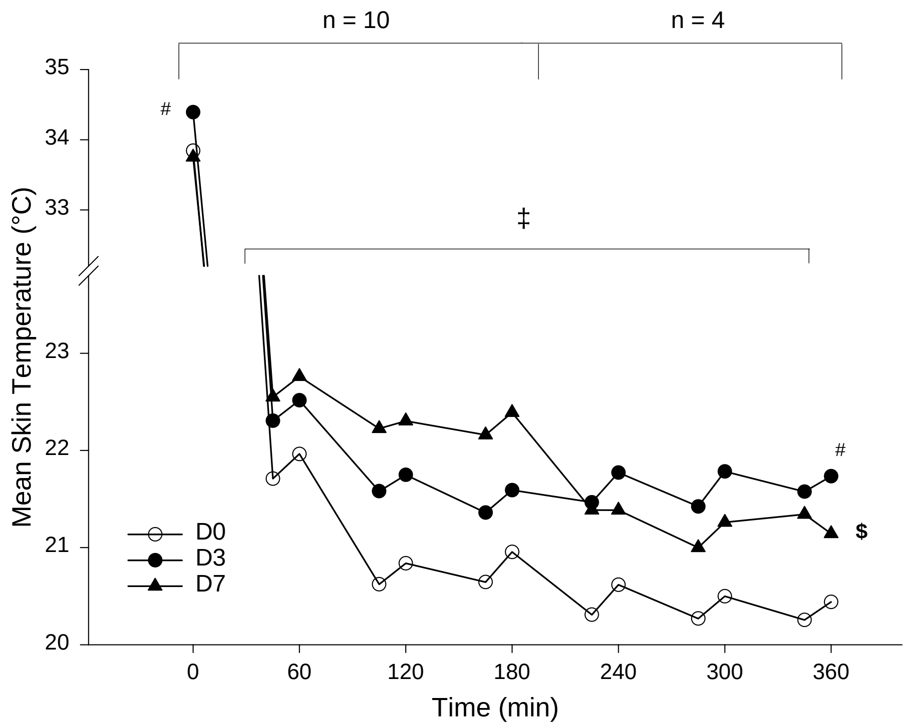

Figure. 5. Mean skin temperature vs. time during cold exposure before (D0, ○), after 3 days (D3, ●) and after 7 days (D7, ▲) of physical exertion. Data from min 0 to min 180 are from 10 subjects and data from min 190 to min 360 are from 4 subjects. ‡, D3 and D7 significantly ($P < 0.05$) different than D0; #, D3 significantly ($P < 0.05$) different than D0 and D7; $, D7 significantly ($P < 0.05$) different than D0.

<u>Metabolic heat production, insulation, heart rate, thermal sensation.</u> Metabolic heat production increased from rest during all 3 cold exposures with no differences among trial days. A higher metabolic heat production was observed during the rest/rain periods through the 3rd rain period on D3, vs. D0 and D7. Whole body insulation was less ($F = 11.62$, $P < 0.01$) on D3 and D7, vs. D0, during the last three hours of cold exposure. Forearm insulation was lower ($F = 8.33$, $P < 0.01$) on D3 and D7, compared to D0, and there were no differences among days for calf insulation. Heart rate was significantly higher (main effect, $F = 4.52$) on D3 compared to D0 during the first 3 hours of cold exposure. Heart rate was similar before and during the first 3 hours of exercise-cold stress. Thermal sensation was similar among trial days during cold exposure.

Blood Responses.

Serum glucose concentrations averaged between 4.5-6 $mmol \cdot L^{-1}$ throughout the study, with no significant differences between groups, trials or measurement times. No hypoglycemia (< 2.7 $mmol \cdot L^{-1}$) was observed. Plasma volume expanded on D3, relative to D0, 15.8 ± 7.1% and on D7, relative to D0, 15.2 ± 5.4%. Plasma catecholamine concentrations measured at 0700-h (basal) and after cold exposure are presented in Fig. 6. Catecholamine concentrations at baseline (0700-h) were corrected for plasma volume changes. Plasma norepinephrine was significantly higher at 0700-h on D3 and D7, compared to D0. Plasma norepinephrine increased significantly ($F = 11.61$, $P < 0.02$) during all three CW, but there were no differences in post-exposure NE concentration among trials. Cold exposure elicited a 3 to 4 fold increase in plasma epinephrine; however there were no differences among trials at 0700-h or post-CW (Fig. 6).

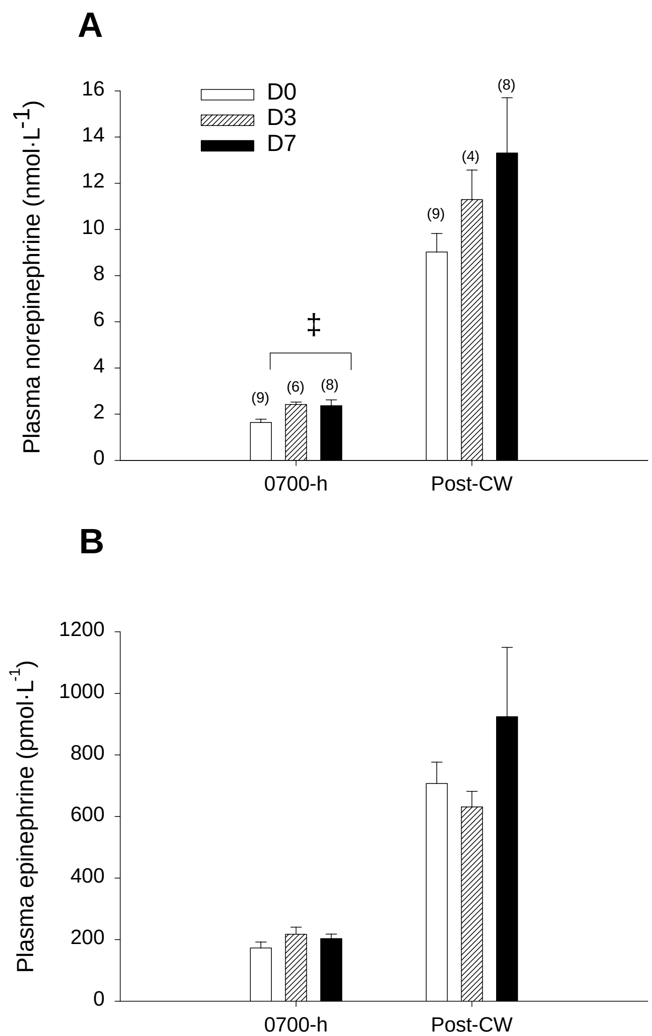

Figure. 6. Plasma norepinephrine (A) and epinephrine (B) concentrations at 0700-h (baseline) and after cold exposure (Post-CW) before (D0), after 3 days (D3) and after 7 days (D7) of exhaustive exercise. Number of subjects for each timepoint for norepinephrine and epinephrine is indicated in parentheses. ‡, D3 and D7 significantly different ($P < 0.05$) than D0.

Discussion

The primary finding from these studies was that when individuals exercised before cold exposure, they cooled faster than when rest preceded cold exposure. However, the data are not consistent with our hypothesis that exercise would lead to "thermoregulatory fatigue" of the shivering response to cold. We had based that hypothesis on our own finding (1) and those reported by others (7, 8, 12) suggesting that shivering can become fatigued. In this study, the shivering response to cold was the same whether or not acute or chronic exercise preceded the cold exposure. In contrast, mean weighted heat flow and skin temperature measurements were higher and, concomitantly, tissue insulation less during cold exposure following exercise. Collectively, these observations indicate that, following either acute or chronic exercise, greater peripheral heat loss from the skin ("thermoregulatory lag" and/or "heat redistribution") was responsible for the greater cooling rates during cold exposure.

Several factors might explain why peripheral heat loss and mean skin temperatures during cold exposure were greater when preceded by acute or chronic exercise. One possibility is that post-exercise

hyperemia in the leg muscles persists during cold exposure, increasing convective heat transfer from the body's core to the periphery overlying active muscle relative to cold exposure preceded by rest ("heat redistribution"). The higher heat flow and lower insulation in the calf during cold exposure following exercise in Study 1, compared to passive heating, are consistent with this explanation. However, the higher skin temperatures observed in Study 2 during cold exposures completed after seven days of exhaustive exercise do not likely represent the "heat redistribution" mechanism. In Study 1, resting cold exposures were completed shortly after (20 min) exercise, so effects of a persistent post-exercise hyperemia would be pronounced compared to the other trial in which resting cold exposures were not shortly preceded by exercise. In Study 2, subjects performed standardized exercise of the same intensity during all the cold exposures, so muscle blood flow, and thus heat redistribution, should have been constant among trials. Thus, we believe that our observations indicate that fatigue induced by exhaustive exercise may indeed blunt the vasoconstrictor response during cold exposure, although the possibility that post-exercise hyperemia contributes to higher skin temperatures cannot be ruled out.

Another possibility is that the prior exercise blunted the sympathetic drive for vasoconstriction normally elicited in response to cold ('thermoregulatory lag"). However, in Study 1, the norepinephrine response to cold was the same whether cold exposure was preceded by exercise or passive heating. In contrast, following chronic exercise (Study 2), the blunting of the vasoconstrictor response to cold subsequent to severe physical exertion may be related to concomitant elevations in basal circulating norepinephrine levels. Opstad (5) has observed higher circulating norepinephrine levels in soldiers following multiple days of exhaustive exercise coupled with sleep deprivation, and Young et al. (17) reported similar effects in soldiers who had just completed an 8-week training course that entailed heavy physical exertion throughout coupled with sleep deprivation and negative energy balance. In this study, we observed that basal norepinephrine levels were elevated in our subjects after three and seven consecutive days of exercise. Despite the elevation of basal norepinephrine concentrations, cold exposure elicited similar sympathetic activation during all three cold exposures, as evidenced by the increment in norepinephrine concentrations observed by the end of each of the cold exposures, the magnitude of which did not differ among trials. Stimulation of adrenergic receptors mediates cold-induced vasoconstriction. Since the increment in norepinephrine was similar during all three cold exposure trials, a blunted sympathetic nervous stimulus does not appear to account for the less pronounced vasoconstrictor response. A diminished sensitivity of the adrenergic receptors remains as a viable mechanism to explain blunting of cold-induced vasoconstriction observed in the present experiments. Chronically elevated norepinephrine levels have been shown to decrease adrenergic receptor sensitivity in animal models (13) and similar effects have been suggested to develop in humans in whom circulating norepinephrine levels remain chronically elevated (5).

The absence of an exercise effect on shivering thermogenesis in both experiments suggests that this response to cold is not easily fatiguable. We observed no difference in the $\bar{T}_b$ vs. ΔM relationship between trials suggesting that the differences in T_{re} between trials were not due to a change in central control of shivering thermogenesis. In Study 1, perhaps the exercise intensity and duration were not sufficient to fatigue the shivering mechanism, which is a relatively low intensity activity, at least compared to exercise. In Pugh's case report of the Four Inn's Walk (7), the participants were exercising up to 20-h in cold-wet conditions. Likewise, the subject in Thompson and Hayward's study (12) who developed shivering fatigue was exercising for 4-h in severe cold-wet conditions. We modeled this exposure in Study 2 and still did not observe shivering fatigue. Another possibility is that shivering impairments observed in these earlier studies may not reflect fatigue, but rather hypoglycemia, which is known to impair shivering (3, 6). Plasma glucose levels were not measured in those previous studies (7, 12). In our studies, plasma glucose concentrations remained normal throughout cold exposure. It may be that exhaustive exercise must be coupled with other factors such as sleep deprivation or caloric deprivation before this thermoregulatory effector response is blunted.

Many subjects, during the chronic exercise experiment, were unable to continue walking for 6 hours in the cold-wet conditions due to muscle cramping (n = 4), leg and knee pain (n = 2), and general muscle stiffness (n = 1). If these volunteers were subjected to wet-cold conditions in a scenario where they could not escape the cold after discontinuing exercise, shivering alone would be insufficient to offset heat loss, and core temperature would fall. Weller et al. (14) and Thompson and Hayward (12) demonstrate this elegantly in their studies when exercise intensity decreases during prolonged cold-wet exposure. Thus, physical

exertion affects the ability to maintain normal body temperatures during cold exposure via both direct (i.e. impairing thermoregulatory response-vasoconstriction) and indirect (impairing capacity to increase metabolic heat production) mechanisms.

In conclusion, this series of studies examined the effects of acute (one hour) and multiple days of exhaustive exercise on temperature regulation during prolonged cold exposure. Our findings demonstrate that following either type of physical exertion, the vasoconstrictor response to cold exposure is blunted, perhaps due to a fatigue-related mechanism. In contrast, shivering thermogenesis appears less sensitive to the effects of previous physical exertion. Increases in peripheral heat loss during prolonged cold-wet exposure associated with impaired vasoconstrictor responses to cold would eventually exacerbate the fall in core temperature, if metabolic heat production is unchanged, thereby increasing susceptibility to hypothermia. These findings have implications for individuals, such as hikers, military personnel, and outdoor workers, who are exposed to cold-wet environments and have been engaged in heavy, fatiguing exercise.

Disclaimer

The views, opinions and/or findings in this report are those of the authors and should not be construed as official Department of the Army position, policy, or decision unless so designated by other official designation. Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USMRDC Regulation 70-25 on Use of Volunteers in Research.

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Cold Condition Influence on the Pulmonary Function in Smoking Military Men

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Summary

Aim: Revealing of latent injuries of airways in smoking military men with age of 18-40 year, who serves from time to time under extreme climatic condition (cold, dry, windy weather on moderate altitude);
Materials and Methods: It was investigated 54 smoker militaries (males, 18-40 years old). The investigation was carried out during 1 year on the permanent place of location of armed unit and on the place of field mission in winter (moderate altitude of Caucasus). It was performed questioning of smoking index and tobacco-dependence. It was investigated respiratory function of lugs, routine hemodinamic and red blood indices. In control group were included healthy nonsmoker militaries from the same military unit.
Results: the investigation showed that in smokers (as heavies as middles) respiratory function tests (FEF_{25}, FEF_{50}, FEF_{75}) decreased significantly after influence of cold, dry mountain air. It means that the pathological process has already begun in small airways.
Conclusions: Smoking is one of most aggressive risk factors of Respiratory Diseases. The usual loading of soldiers: moderate physical activity under the extreme climatic conditions (cold, windy air of moderate altitude), may be the provocative testes for lung diseases in the so-called "healthy smokers". The level of change of Respiratory Functional Testes in smokers mainly depends on smoking index, hereditary abundance, predisposition to allergy and constitutional qualities.

Key Words: tobacco, smoking, small airways, moderate altitude, and cold air.

Introduction

The relationship between human organism and an environment is determined by nature as harmonic. Homo Sapiens, by means of his mental abilities, always - during the evolutionary process, created a lot of problems of adaptation to his environment and tried at the same time to improve them.
Many risk factors, such as: industrial pollution, radiation, tobacco, alcohol etc. are the products of civilization and they cause various diseases or induce their manifestation. The essence of disease is a disbalance between the human organism and an environment. "What is an illness, if not Freedom Restricted Illness" - wrote Marx. But the freedom of health is human organisms' capacity to adapt to

stressful environmental factors, to defend himself and to auto regulate. It is difficult to divide strongly health and illness. We can only try to expose beginning of the pathological process in concrete person. Just this is a main idea of our work, the fragment of which I would like to present you. It includes an investigation of adaptive process among soldiers of Georgian Army, exposure of risk groups of various diseases, and tries to improving their military life and service standards.
In the Georgian Army there are many problems and one of them is smoking. According to previous investigation carried out with help of the special "Smokers Questionnaire"(2, 4), it was shown that 76% of Georgian military personnel are smokers, but among soldiers this index reaches 85%.
It is known that smoking, as an aggressive risk factor, causes and supports the progress of numerous diseases. In spite of this, for most people it is very difficult smoking cessation. In cigarettes there are about 2000-4000 different harmful products; among which the most harmful are: Nicotine, Irritants (acrolein, aldehids, soot etc.), Carcinogens etc.
Smoking injuries the whole organism, mainly Cardiovascular (CS) and Respiratory systems (RS). The Chronicle Obstructive Pulmonary Diseases (COPD) are mostly widespread diseases of RS caused by tobacco, developed among 15-20% of smokers. It is known that much before the manifestation of bronchoobstructive syndrome, reversible and than irreversible process begins in small airways (below 2-mm diameter), which are responsible for total pulmonary resistance in 20% and in 99% they are the components of total airways-volume. Early revealing of these pathological changes is very important for prevention and treatment of COPD and other chronicle lung diseases.
Extreme environmental factors, such as: cold windy weather, industrial pollution, physical exercise etc. often cause the latent respiratory pathology. In our work we have used as such extreme factors: natural winter cold dry air of the Caucasian moderate altitude and moderate physical exercise in these conditions. With help of them we tried to exposure the airway pathology among smoker individuals, which are regarded as healthy, because by routine medical examination in normal conditions didn't is founded any pathology.

Materials and Methods

54 military persons are investigated: smokers military men from the Unit of Georgian Terrestrial Armed Forces, which is located near Tbilisi, in borough *Kojori* (higher from sea level - 1350m; middle annual temperature: 7,4˚C; middle winter temperature: -2,6˚C; climate: demp subtropical. The service of these militaries includes the short missions to different regions of Georgia. Among them are the regions of moderate altitude of Caucasus: Kazbegi, Svaneti, Thousheti, Javaxeti (there are not included the summits of these regions). Their common middle characteristic: higher from the sea level: 2000-3200m; climate: cold continental; middle annual temperature: -1,2˚C; middle winter Temperature: -15,2˚C, often windy (speed: 15-20m/sec). The field missions had been performed by the small groups (6 persons). Each of them performs this mission twice per cold season. During this mission they have some moderate physical activity (climbing, walking etc). The control group included 25 healthy nonsmoker men from the same unit.
Smoking index and *tobacco-dependence* were evaluated by special questionnaires: K. O. Fagerstorm's, 54-item smoker's questionnaire, smoking index formulae (2, 4). Beside this they have been questioned with purpose to establish other risk factors, as a hereditary abundance, allergy and frequent airways acute inflammatory diseases in anamnesis and have been made routine clinical examination.

During observation were used such Respiratory Functional Tests:

- Lung Vital Capacity (LVC)
- Forced Vital Capacity (FVC)
  (It was investigated on the Spirograph
- Forced expiration Volume in 1st second (FEV1)
  Forced Expiratory Flow between 25, 50 and 75 % of FVC (FEF_{25}, FEF_{50}, FEF_{75}) (Fig. 1)

  (It was investigated on the portative Flowscreen "Jeger")

  The blood oxygen saturation was been determined on the portative "Pulsoximeter 540".

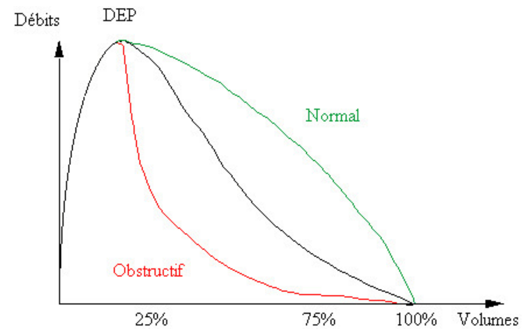

Figure 1

Dynamic study of hemodynamic (HR, T/A) and red blood indices (Hb, Er, Fi, Ht) was also performed.

These investigations were performed by stages:

- At the place of permanent location of the Military Unit- Kojori, in moderate climatic condition: in September;
- At the place of field mission: on the moderate altitude, in winter, twice, immediately after exercise (ascent and descend of ≈500−700m of terrestrial level).
- At the place of permanent location- in Kojori, immediately on return from the mission.
- One year later after beginning of our observation.

Results and Discussion

According the previous investigation: questioning, routine clinical examination, - we have determined two main subgroups:

1. "Healthy Smokers" -- among which we could not find any pathology: 37 persons (68,5%).
2. "The group of Prebronchitis"-- persons, who have not had complaints but they sometimes had matutinal cough and offensive nonproductive or productive cough caused by some factors: inhalation of cold air, cold drink, hard physical exercise, emotional stress etc.; and have in anamnesis (during last 2 year) 3-4 times and over acute airway inflammatory diseases: 17 persons (31,5%).

19 persons (36%) from both subgroups had initially decreased FEF_{50} and FEF_{75} (authentic, $p<0,005$).

According data of Fagerstorm's 6-item questionnaire of tobacco-dependence, it was determined three groups:

1. Light tobacco-dependence, - in 25 persons (46,5%);
2. Middle tobacco-dependence, - in 20 persons (37,8%);
3. Heavy tobacco-dependence, - in 9 persons (16,7%)

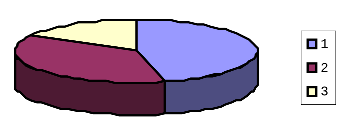

Fig 2

Two groups were determined by smoking index ():

1. Middle smokers -42 person (77%)
2. Heavy smokers - 12 persons (23%)

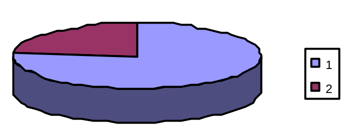

Fig 3

The investigation of respiratory functions at moderate altitude, cold windy weather, under physical activity, showed that in the 1st subgroup FEF_{50-75} was decreased in 36 % (p< 0,01); and FEV1 was decreased in 18%, but not authentically (p<0,1). FEV1/FVC remained on normal level - 70-75%.

Table 1

Index	Permanent place - Kojori Oct. (alt_ 1350m, middle tº_15ºC) %	Permanent place - Kojori Jan. (alt_ 1350m, middle tº_ -2,3ºC) %	Mission place - January (alt-2700, middle tº_-16ºC) %	Permanent place - Kojori, 1 year later, Oct (alt_ 1350m, middle tº_15ºC) %
VC	104.12 ± 1.82	98.78 ± 1.01	96.72 ± 1.4	103.25 ± 1.2
FEV1	102.70 ± 1.86	98.67 ± 1.01	89.37 ± 1.9	96.22 ± 1.8
FEV1/FVC	72.17 ± 0.67	70.23 ± 0.69	68.83 ± 0.97	73.86 ± 1.54
FEF_{75}	99.05 ± 0.81	97.85 ± 1.04	82.21 ± 1.82	83.14 ± 1.6 *
FEF_{50}	102.65 ± 1.72	96.86 ± 1.01	79.25 ± 1.71 *	79.25 ± 1.4 *
FEF_{25}	99.56 ± 1.75	97.79 ± 0.97	86.79 ± 1.9	89.12 ± 1.8

(*- Authentic data)

In the second subgroup (group of "Prebronchitis") decrease of FEF_{25-75} was authentic in 67% - 12 persons (p<0,005). Decrease of FEV1 and FEV1/FVC was authentic in 33% of 2nd subgroup (p<0,01).

Table 2

Index	Permanent place - Kojori Oct. (alt_ 1350m, middle tº_15ºC) %	Permanent place - Kojori Jan. (alt_ 1350m, middle tº_ -2,3ºC) %	Mission place - January (alt-2700, middle tº_-16ºC) %	Permanent place - Kojori, 1 year later, Oct (alt_ 1350m, middle tº_15ºC) %
VC	101.18 ± 1.62	99.73 ± 1.01	95.72 ± 1.40	98.25 ± 1.68
FEV1	97.76 ± 1.86	94.67 ± 1.01	86.37 ± 1.92	81.22 ± 1.80*
FEV1/FVC	72.17 ± 0.67	70.23 ± 0.69	68.83 ± 0.97	67.86 ± 1.54
FEF_{75}	89.05 ± 0.81	92.85 ± 1.04	76.21 ± 1.82 *	79.14 ± 1.60*
FEF_{50}	85.65 ± 1.72	96.86 ± 1.01	72.25 ± 1.71 *	77.76 ± 1.42*
FEF_{25}	95.56 ± 1.75	92.79 ± 0.97	76.79 ± 1.90	71.12 ± 1.89*

During field missions a few soldiers had some clinical manifestation of bronchitis: one had an attack of bronchospasm, which was suppressed immediately after salmeterole inhalation. 8 persons from both groups had an episode of offensive nonproductive cough (by lung auscultation: expiratory dry wheeze). 5 persons got pharyngitis.

These changes showed that could and dry air serves as a provocative test for middle and heavy smokers and latent bronchoobstructive syndrome was manifested.

The investigation, made 1immediatelly on their arrival in Kojori, showed that FEV1, FEV1/FVC improved in couple of days, but the change of FEF_{25-75} partially remained during 7-10 days.

Repetitive investigation, made 1 year later from the beginning our work, showed that in 12 persons from both subgroups (particularly from 2nd - 9 persons FEF_{25-75} was authentically decreased (p<0,005), compared with initial data. But the changes of other tests were not authentic.

Hemodinamic data and changes of HR and T/A during this observation period were adequate, quite normal. Blood oxygen saturation also was normal and adequate during this period.

In control group all data were normal (except 4 cases when soldiers got acute respiratory viral infection and have been removal from investigation).

It is notable that

1. Some persons from second group cessated smoking. By last investigation it was shown that their respiratory indices are not decreased.
2. In 25% of both subgroups the LVC and FVC increased. We think that it was caused by physical activity on mountain fresh air.

The blood oxygen saturation, HR, T/A, red blood indices (Hb, Ht, Fi, Er) remained on the normal level and has changed adequately according constitutional and age norms. It means that lung alveolar respiratory function had been normal yet.

According to our investigation data, it is clear that smoking damages small airways quite early (decrease of FEF_{25-75}) and not only among heavy smokers.

Among those who clinically developed bronchoobstructive syndrome were mainly heavy smokers, with heavy tobacco-dependence, and persons with hereditary and anamnestic abundance.

Conclusions:

1. Smoking is one of most aggressive risk factors of Respiratory Diseases. Particularly for Chronicle Obstructive Pulmonary Diseases (COPD);
2. The usual loading of soldiers: moderate physical activity under the extreme climatic conditions (cold, windy air of moderate altitude), may be the provocative testes for lung diseases in the so-called "healthy smokers".
3. The level of change of Respiratory Functional Testes in smokers mainly depends on smoking index, hereditary abundance, predisposition to allergy and constitutional qualities.
4. Among smokers the damage of small airways develops quite early and after some times this becomes irreversible. Determination of this time is very difficult. Therefore it is very important to early smoking cessation, to devise especial individual exercise and diet regimen for the rehabilitation of former smokers.

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Adaptation of the Vessel Wall Functional Activity in Young Smoker Men in Cold Altitude Climatic Zone

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Summary

The vessel wall functional activities reserve capacity was performed using venous cuff test in smoker militaries. The test was combined with 10-min. venous occlusion on the arm. The comparative study was conducted in smoker and non-smoker militaries in different climatic and terrestrial condition. Using the series of laboratory tests on haemostasis system depression of the fibrynolisis system in smoker militaries have been detected in its baseline activity as well as in high altitude zone.

Key words: venous occlusion test, fibrinolysis activity, vascular disorders, smoking, climatic condition, and altitude zone.

Introduction:

Clinical experience suggests that many physicians harbor a misconception regarding the pathogenesis of thrombotic disorders, particularly in those individuals with recurrent episodes. Patients are often evaluated for ”hypercoagulobility ”with a multitude of coagulation and platelet function tests, as if its detection would account for the cause of the thrombosis. This misperception has the potential of obscuring the true cause of the thrombotic problem, and the investigative approach it generates often results in a battery of costly coagulation tests, many of which have little bearing on the underlying problem.

Approaching the path physiology of thrombotic disease on the basis of Virchow’s triad, rather than on the basis of the primary or secondary abnormalities of hemostasis , provides a better conceptual foundation on which to base an investigation (1,2).

Virchow postulated that trombosis results from abnormalities of blood vessel, abnormalities of blood flow, or of abnormalities of blood constitution. This simple but broad concept retains its validity today and forms the basis for an understanding of the pro-thrombotic state.

Using Virchow’s theory one can implicate any one or a combination of the tree elements in the pathogenesis of thrombosis or the creation of a pro-thrombotic state. However, by necessity a disturbance in any one of the limbs of this triad must activate and proceed through the hemostasis mechanism, the final common pathway to thrombosis.

The fibrinolysis system is considered to play an important role in many physiological and pathological processes (6). However, a great deal of the experimental data has been obtained with methods (e.g. fibrin-plate lysis, whole blood clot lysis time or euglobulin clot lysis time), which are difficult to perform and are uncertain in terms of what they really measure. In view of the rapid progress in our knowledge about the fibrinolytic process and its regulation there is a great demand for more specific methods to assay its individual activation at different condition. Therefore, it is interesting to take in consideration the mosaic

character of the haemostasis system, for example, tissue plasminogen activator in arms are several time more than in legs vessel endothelium. Several plasminogen activators contribute to total fibrinolytic system.
For the plasminogen release from the endothelium study the venous occlusion test of the arm is widely used. In previous period (4,7) there was used venous stasis of 20-min duration. However, the ensuing pain experienced by the patients has been the major obstacle for its repetitive use. According to other authors results we accepted 10-min occlusion yielded results which were equally informative as those obtained 20-min while causing loss discomfort for the patients. Therefore, the individuals exhibited their peak activity after 10 min.
The results come from the same researchers who has show that venous cuff test using in small groups is equally informative and important for the vascular wall functional activity evaluation and its individual difference detection (3).
It have been detected that formation of plasmin measured as increased in plasmin-antiplasmin complex is obtained to a much larger extend by venous occlusion than exercise the activator content in the latter samples was somewhat higher. The reason for this is not known, but one can speculate that exercise activates also the coagulation cascade, thus producing fibrin, which may stimulate the plasmin activator.
It have to be note, that vessel’s reflex zones with the hemo- and baro-receptors represents the local regular system. Also, muscles and internal organs produce thrombolytic ingredients and fibrinolysis activators. Thus, under the cold temperature or either in the terrestrial elevation, as well as hypoxia, the stress reaction exists as the necessary human adaptation to environment and depends to the duration of the stress.
Humor factors (hypercatecholaminemia, erythremia, milk acid concentration increase, etc) have a same influence on the microcirculation. There have been considered (5) that the major risk factors to the altitude disease (elevation on zone higher than 2000 m.) exhibition are as follows:
quickly elevation, young age, physical load, chronic pulmonary disease, alcohol take.
Concerning the previous data it have been detected that cigarettes can trigger depression of the vessel wall endothelium prostacycline capacity. Smoking not only chronically increases thrombogenic risk, but it also an abrupt short-term risk. Over the long term, smoking damages the protective living inside blood vessel, making them more susceptible to plaque formation. More immediately, smoking causes blood vessel to constrict and stimulates platelets to form clots
Therefore, based on the multifactor prospective studies and angiografic investigations it have been detected that smoking is an independent risk factor of major vascular diseases.

Material and methods:

The vessel wall functional activity and its reserve capacity have been evaluated in smoker militaries with peripheral vessel disorders (vascular acrosyndroms, acrocyanose, Livedo reticularis, Raynod’s phenomenon, acrorhigose, acrocholose). The diagnosis was made clinically and due to nitroglycerine-test performance.
Militaries were assigned to the Georgian Army in Tbilisi with the altitude level about 500 m.(I group) - 34 persons in age 18-29 years.
The second group was combined with same personnel, temporary sent on a mission (during 5-7 days) in the region with terrestrial elevation above 2500-3000 m. and average winter temperature –10-25 C.
Only healthy non-smoker militaries (10 men) were used throughout this study as a control group, who were all well informed of the nature of the investigation.
To determine baseline fibrinolytic activity volunteers and patients were resting 30 min.
Venous occlusion was obtained by placing at the upper arm a cuff inflated midway between systolic and diastolic pressure. Prior to and after the stasis for 10 min. a blood sample was occasionally drawn from the same arm. The plasma samples were collected with precaution to prevent any contact activity and care was taken that blood flowed easy to avoid contact phase activator. The blood was centrifuged for 20 min. at 2500 to obtain platelet-poor plasma. The following haemostsis system parameters have been detected: circulated fibrinogen, fibrinogen-B, fibrinolysis activity, antithrombin III activity, kallekrein-kinin frozen test, prothrombin activity.
For the microcirculation capacity evaluation, as well as for the blood vessel organic or functional damage difference, generally accepted nitroglycerine test have been performed. The nitroglycerine test has been done in 25 persons using sublingual nitroglycerine administration in dose 0,5 mg. and accomplished rheovasogram.
Statistical evaluation was done by the paired Student t-test.

Results:

The positive Nitroglycerine test was exhibited in all of the patients.
The mean basic rheovasogram's index in smoker patients with Raynod's syndrom on the left hand was 0,398 ± 0,078, on the right hand 0,386 ± 0,07.
After 2 min. nitroglycerine administration the rheovasogram index was increased to 0,628 ± 0,121 on the left hand and to 0,599 ± 0,121 on the right one.
During the following 3 min the successive increase of the index has been detected – 0,743 ± 0,145 on the right hand and 0,812 ± 0,155 on the left hand. The basic fibrinolytic activity (blood sample taken after 30 min. rest). in the first group's persons has been increased in 23% cases as compared with the control group with the fibrinolysis pronounced increase in 48%. After the venous stasis 71,5% of the patients showed decrease of the fibrinolysis instead 16% in the control group. No change has been detected in 15,5% in the experimental group and in 36% in the control one. (Figure 1,2)

Fig. 1

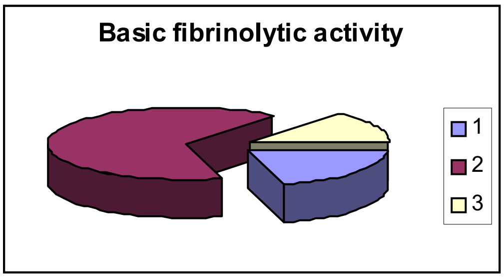
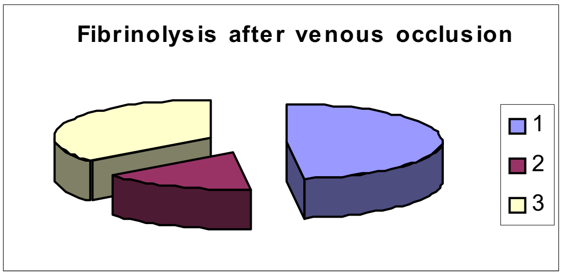


Fig. 2



1- Fibrinolysis increase; 2-fibrinolysis decrease; 3-no change

The mean basic fibrinolys activity was estimated as 23,0 ± 6,07% in the first group and as 17,5 ± 5,93% in the control.
After the venous occlusion all subject of the first group showed decrease of the fibrinolysis activity ranging to 16,86 ± 5,92% and in the control group an increase to 19,5 ± 7,51%.
Concerning to the other haemostasis system parameters (table1) it have to be noted that significantly pronounced alteration have been exhibited in the fibfinogen-B basic concentration in the patient's group: (7,55 ± 0,61 g/l instead 5,51 ± 0,99 g/l in the control), as well as in the antithrombin III level (35,14 ± 3,05% and 43,83 ± 3,41%, accordingly). After the cuff test the difference in fibrinogen-B concentration has been increased to 8,56 ± 0,54 g/l in the first group, so it was significantly higher as among healthy person.
Antithrombin- III's level in the postocclusion period was pronounced increased in the healthy militaries ranging to 43,33 ± 2,97% as comparing to the smokers with antithrombin -III level equal to 34,43 ± 2,69%.
There was also detected kallekrein-kinin's bridge alteration in both groups with the tendency to compensate minimization: 16,71 ± 6,72% prior to and 11,92 ± 3,46 after occlusion in experimental group and 18,57 ± 5,96 and 10,02 ± 2,17 in control.
Thus, the release of the tissue plasminogen and antithrombotic factors in response to venous occlusion differs considerably among healthy and patients with vascular disturbances. No significant difference was found in the prothrombin activity, thrombocytes aggregation, circulate fibrin-monomeres or circulate fibrinogen.
According this data, we choose to implement more informative parameters for the vessel wall functional activity evaluation in the high altitude zone. All samples before and after vascular occlusion were also analyzed in same persons from the control and patients groups.
It have to be note, that only in 7,8% patients with vascular disorders the fibrinolytic activity has been increase, instead 21% in healthy person. The mean basic fibtinolys activity was estimated as 18,01 ± 4,23% in I group and as 21,14 ± 6,43% in the control group. Immediately after venous occlusion the fibrinolytic activity has been decrease to 16,43 ± 5,67% in the experimental group. In the healthy person it was somewhat higher increased to 23,14 ± 6,17%.

Venous occlusion influence on the hemostasis parameters

Table 1

Hemostasis parameters	Prior to venous occlusion		After venous occlusion duration 10 min.		P_{3-4}
	I group n1	Control group n2	I group n3	Control group n4	
Prothrombin activity in %	18.86±0.59	16.67±0.61	18.57±0.46	16.5±0.79	
Thombocytes spontaneous activity in %	7.7±2.24	9.0±2.04	8.0±0.46	8.5±2.19	
Fibrinogen in g/l	3.67±0.32	3.14±0.44	3.99±0.37	3.47±0.39	
lFibronogen-B in g/l	7.55±0.61	5.51±0.099	8.56±0.54	6.07±1.01	<0.05
Fibrin monomers in opt.un.	0.35±0.02	0.31±0.05	0.36±0.03	0.32±0.03	
Fibrinolysis activity in %	23±6.07	17.5±5.93	16.86±5.92	19.5±7.51	
Antothrombin activity in %	35.14±3.06	43.83±3.41	34.43±2.69	43.33±2.95	<0.05
Kallekrein-kinin bridge in %	16.71±6.72	11.92±3.46	18.57±5.96	10.0±2.17	

Conclusion:

The approach to the evaluation of a pro-thrombotic state can be summarized as follows: multiple risk factors for the development of thrombotic disease exist. These factors mediate their pathophysiologic effect through one or number of the elements of Virchow's triad, and the final common pathway leading to clot formation is through the activation of the hemostatic system (2). A primary abnormality of hemostasis should not be expected in every patient with recurrent thrombosis, but when suspected, defects in the inhibitory mechanisms should be sought.

For a long time it has been known that blood fibrinolytic activity is increased during venous stasis and exercise. It has also been reported (6) that this is due to release of the tissue plasminogen activator from the endothelium cells in the vessel, probably because of the ultrafiltration and haemoconcentration as a result of the venous stagnation.

Evidence of sub clinical activation of hemostasis may occur with primary inhibitory deficits, but such activation often suggests a secondary state of hypercoagulobility. It is important to remember that the majority of individuals who develop thrombotic disease probably do so as a result of blood vessel or blood flow abnormalities with no disturbance of the hemostasis system, except only transiently at the time of the clinical event.

Research work has given the possibility to eliminate an increase of the fibrinolysis activity after the 10 min. of the stasis in healthy volunteers, which was significant compared to its basic activity. However, there were pronounced individual difference of the vessel's endothelium responsiveness to hypoxia condition in the smoker militaries with accomplished vascular disorders. For this reason, it is advisable to conduct 10-min. venous occlusion test. If abnormalities are obtained, as a result of the fibrinolysis depression, it remains to be established which prophylaxis provides the normalization of the vascular wall functional activity (physical activity's increase, stop smoking, antioxidants drug therapy, the elevation regimen's optimization, such as elevation on 300m. during the day).

We have many best way to help smoker people quit now and to protect them against thrombogenic disturbances. And may be those better ways plus this way of explanation what's really going in their blood, might be an additional help to the young smokers.

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Sustaining Hydration in Hot Weather

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Summary

Maintenance of water and electrolyte balance is important for sustaining optimal performance. Dehydration produces greater thermal and cardiovascular strain during prolonged work; with the magnitude of added strain proportional to the magnitude of water loss. Dehydration also degrades morale and the desire to work. Body water deficits of as little as 2% normal body mass have been accompanied by impaired cognitive and physical performance. Furthermore, water deficits of 5% to 7% of normal body mass are generally associated with dyspnea, headaches, dizziness, and apathy.

This presentation will summarize work that the U.S. Army Research Institute of Environmental Medicine has been doing to sustain proper hydration of soldiers during training.

Military Doctrine and Hydration

For the past 15 years, the U.S. military doctrine has taught the soldier that hydration is essential for health and performance, and soldiers should drink frequently to prevent heat injury. The warfighter is encouraged to view water as a tactical weapon. The doctrine further teaches the soldier that if they avoid dehydration they will prevent heat injury and be better prepared to perform their mission. The emphasis on preventing dehydration has led the U.S. Army to adopt a one-size-fits-all drinking schedule for hot weather training, and mandatory or enforced drinking practices in the regimented training environment (e.g., basic training).

The emphasis on drinking as a heat injury prevention practice has been associated with a relatively low incidence of hospitalizations from heat illness. As illustrated in Figure 1, with the exception of the time period encompassing the Gulf War conflict, the rate of hospitalizations from heat illness over the past decade has been below 50 cases per 100,000 soldier-years.

During the same period, however (Figure 1), there has been an increased incidence of hospitalizations from hypoosmolality and hyponatremia, with incidence rates of approximately 10 cases per 100,000 soldier years during the early to mid 1990s. In 1997, The U.S. Military realized the potential medical consequences of hyponatremia and overhydration when a young healthy soldier died consequent to excessive water intake during basic training (2). The death of this young man as well as an outbreak of other less severe symptomatic hyponatremia cases at Fort Benning, Georgia, led to an investigation of the training practices at Fort Benning as well as the Army. Participants in this investigation were staff from the U.S. Army Center for Health Promotion and Preventive Medicine, The U.S. Army Research Institute of Environmental Medicine, as well as staff of Martin Army Community Hospital, Fort Benning.

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

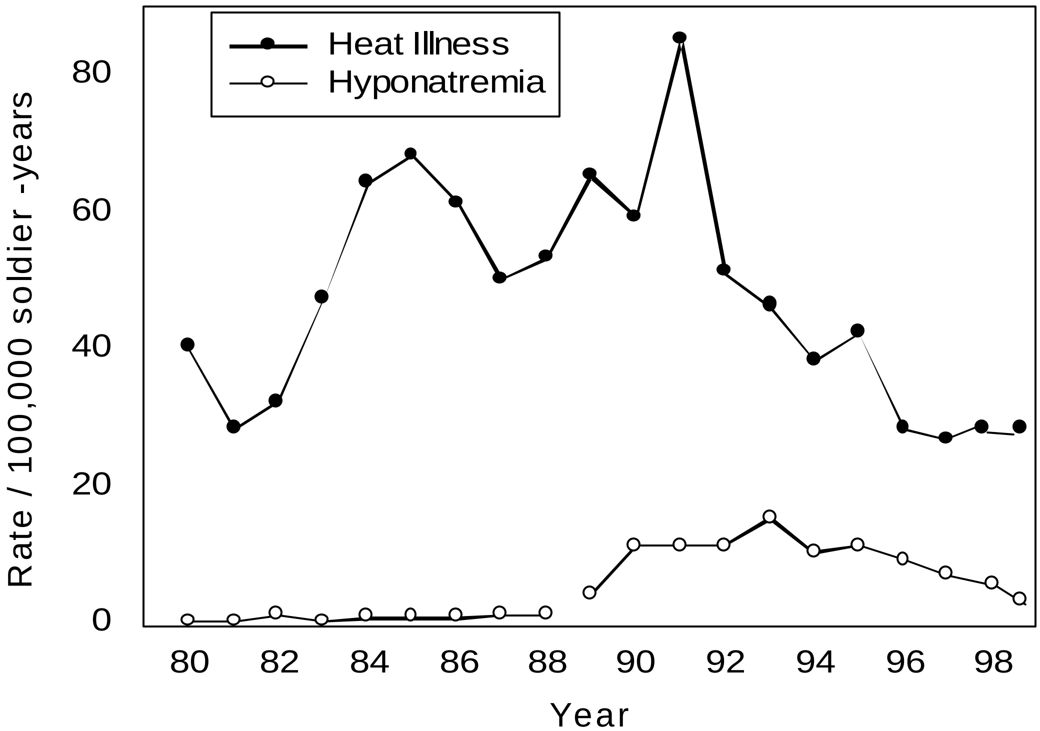

Figure 1. Army Hospitalizations due to Heat Illness & Hyposmolality / Hyponatremia 1980 - 1999

Hyponatremia

The term hyponatremia is strictly defined as a serum sodium level below 135 mEq/liter. However, the term is also used clinically to refer to the syndrome that can occur when there is rapid lowering of blood sodium usually to levels below 130 mEq/liter. In 57 case reports in the literature, serum sodium concentrations at presentation averaged 121 mEq/liter and ranged from 109-131 mEq/liter (6). Signs and symptoms of hyponatremia include confusion, disorientation, mental obtundation, headache, nausea, vomiting, aphasia, incoordination, and muscle weakness. Complications of severe and rapidly evolving hyponatremia include seizures, coma, pulmonary edema and cardiorespiratory arrest. While the condition is generally treatable without long term sequelae, death has occurred (2,7).

The symptomatic hyponatremia of exercise arises consequent to prolonged work (typically longer than 6 h) where sweating is the primary means of dissipating heat. As sweat not only contains water, but small quantities of electrolytes, there is a progressive loss of water, sodium, chloride, and potassium. Sweat electrolyte losses contribute to the development of the syndrome, particularly if sweat sodium losses are high. The condition may also occur when individuals consume low sodium or sodium-free water in excess of sweat losses during and/or shortly after completing exercise. In either case, the reduction in solute concentration in the extracellular fluid (ECF) promotes movement of water from the ECF into cells. If this fluid shift is of sufficient magnitude, and occurs rapidly, it can congest the lungs, swell the brain and alter central nervous system function. Figure 2 presents the physiological consequences of hyponatremia.

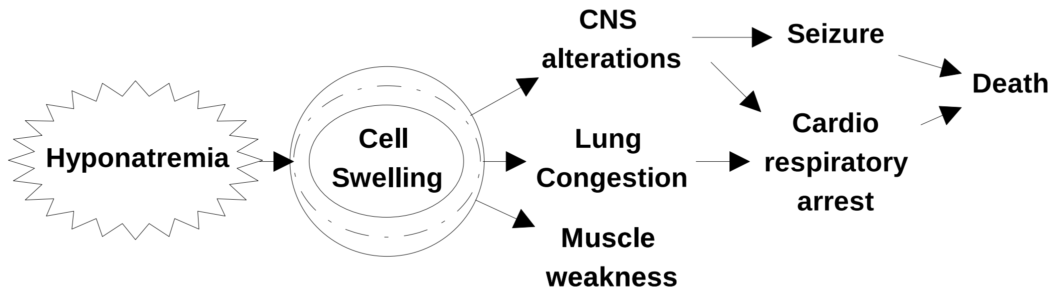

Figure 2. Physiological consequences of hyponatremia

To identify the factors that contributed to the outbreak of symptomatic hyponatremia in the U.S. Army and in particular at Fort Benning, Georgia, the medical records for all cases that occurred during the 1996 and 1997 training periods were obtained and a descriptive analysis was performed (1,7). Examination of the case histories of 17 soldiers hospitalized at Ft. Benning for hyponatremia revealed that all cases were from the student population (i.e., basic trainees). Seventy-seven percent of cases occurred during the first 4 weeks of training and the soldiers were generally healthy the days preceding becoming ill. All were associated with excessive water intake during training compared to water intake requirements predicted based on exercise intensity and weather conditions (3) (8). The excessive water intake was not due solely to voluntary intake or scheduled enforced drinking. Poor medical management also contributed to excessive fluid intake. When soldiers reported that they did not feel well, supervisory personnel often treated the symptoms by forcing additional hydration.

The consultation team recommended two revisions to training practices at Ft. Benning. First, they recommended that the guidelines in use at Ft. Benning be revised to provide more appropriate guidance on fluid intake during activity. Further, the committee also recommended that medical evacuation procedures be revised to more rapidly remove soldiers from training when they exhibited heat illness symptoms.

The fluid intake guidance in use prior to the soldier's death provided recommendations for hourly work and rest as well as drinking when training was conducted in hot weather. The old guidance took into account only the weather conditions and not exercise intensity. It was decided that the new guidance should recommend hourly work and fluid intake based both on the climate and exercise intensity. In addition, upper limits to hourly fluid intake and daily fluid intake should be included in the revised drinking guidance.

Revision of Fluid Replacement Guidelines

To construct the new fluid replacement guidelines, we first used the USARIEM heat strain model (8) as well as the Scenario model (3) to predict hourly work duration and the sweating rates for light, moderate and hard work (250, 425 and 600 Watts) under hot weather conditions ranging from 30 to 35°C wet bulb globe temperature. A table providing hourly work: rest recommendations as well as recommended water intake for three levels of work intensity for 5 hot weather categories was then generated. The predictions were then tested in a series of laboratory experiments where soldiers worked and drank as specified in the revised guidelines for a range of weather conditions. The table was then adjusted as necessary. The specific details of the modeling effort and the validation experiment are published elsewhere (5).

To determine if the revised guidelines had the desired effect of limiting incidence of overhydration but not promoting dehydration, blood samples and body weights were measured before and after 8-12 hour of military training under the old and new fluid replacement guidelines (4). The investigation was performed in two phases, August-September in 1997 and July-August, 1998. A total of 613 soldiers participated in the investigation. All were members of fourteen training platoons engaged in military basic training (six platoons in 1997 and 8 in 1998). The platoons were selected based on their training plans to include different

activities with a wide variety of metabolic rates. Daily wet bulb glob temperatures averaged 27±2°C (range 23±2°C to 33±2°C) and 27±1°C (range 20±1°C to 30±1°C) in 1997 and 1998, respectively. Each platoon was studied on one occasion. In each phase, the leaders and soldiers had received instruction on the respective water replacement guidelines by their instructors and medical officers earlier in the summer. The platoons performed activities according to training schedule and consumed fluid ad libitum or as directed by the platoon leader. The investigative staff did not enforce the guidelines in 1997 or 1998 data collection periods.

The results of this comparison suggest that the revised fluid replacement guidelines are reducing the incidence of overhydration among the training population. When training under the old guidelines, plasma sodium levels modestly declined from morning to afternoon (137.5±1.6 mEq/liter to 137.1±2.0 mEq/liter). Under the new guidelines, plasma sodium levels were initially higher ($P<0.05$) than under the old guidelines and modestly increased during training (139.0±1.7 to 139.4±2.15 mEq/liter). There was also a lower incidence of sodium levels falling greater than 2 mEq/liter (1 sd from the mean) under the new fluid replacement guidelines (Figure 3). Fifteen percent (42 of 273) of soldiers training under the old guidelines had greater than 2 mEq/liter reduction when training under the old guidelines while only 8% (22 of 277) of soldiers had greater than 2 mEq/liter reduction under the new guidelines ($\chi2=26.4$; $P<0.05$).

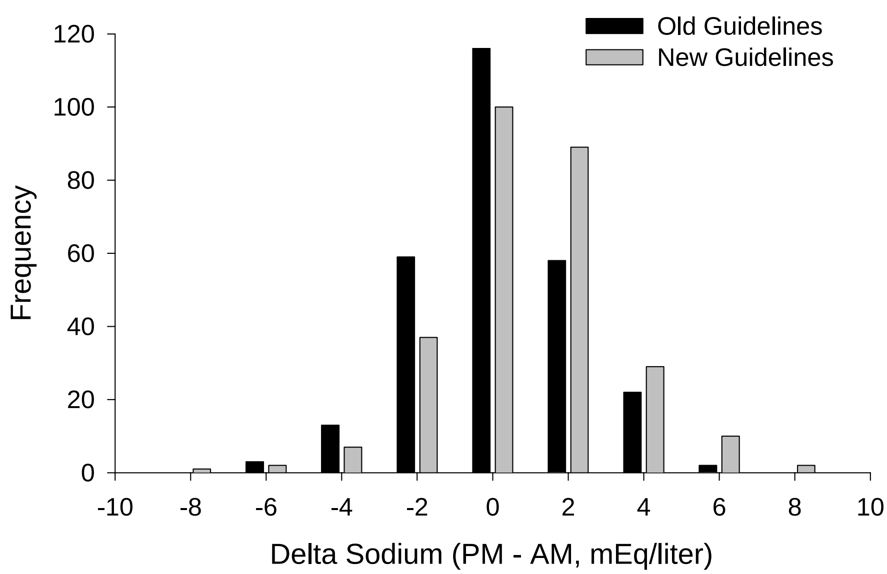

Figure 3. Frequency distribution of plasma sodium change when drinking using the old and new fluid replacement guidelines

Body mass changes between the two populations also support the contention that the revised fluid replacement guidelines improved hydration practices. The soldiers studied in 1997 had a body weight increase during the training day (75.2±10 kg to 76.5±9.9 kg). Less than 1% of the subjects lost more than 3% of body mass, whereas 30% of soldiers gained greater than 3% of their initial body mass during the training day. In contrast, the soldiers studied in 1998 had a smaller body mass gain (74.6±10.6 kg to 75.0±10.7 kg) during the training day and fewer soldiers gained greater than 3% of their initial body mass during the training day (4 of 311 soldiers; 1.6%). Training under the revised guidelines did not appear to increase incidence of dehydration (based on body mass changes) as less than 1% of soldiers had a body mass loss greater than 3% over the training day.

Another way to assess the effectiveness of the fluid replacement guidelines is to look at the incidence of hyponatremia hospitalizations since the revisions were put into effect. Figure 4 presents the incidence of hyponatremia / overhydration hospitalizations from 1997 to 1999 for U.S. Army posts that had 2 or more cases of hyponatremia in 1997. Since the introduction of the guidelines, there has been a progressive reduction in the number of hospitalizations (9).

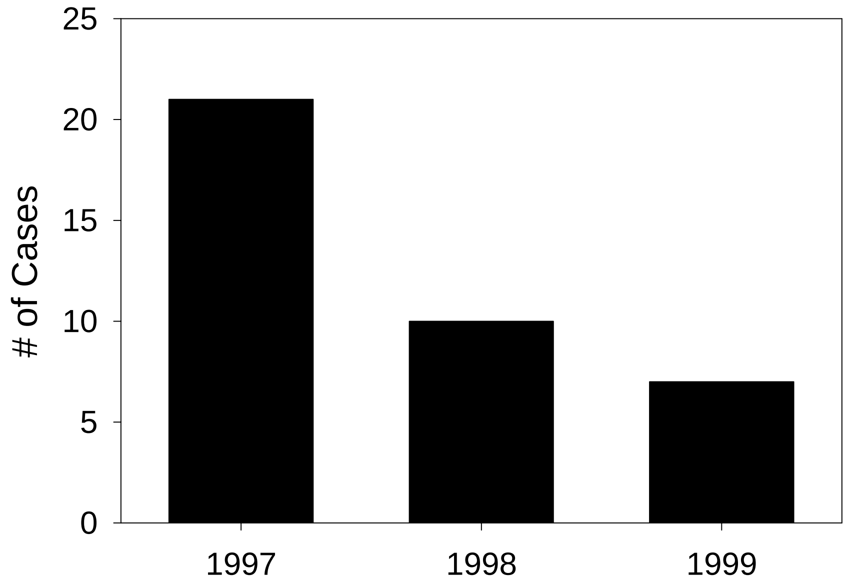

Figure 4. Hyponatremia / overhydration hospitalizations from 1997-1999 for U.S. Army Posts have 2 or more cases in 1997

Sustaining Hydration in Combat

In the field or combat environment, hourly drinking rate guidance is not as relevant as planning for daily water requirements. Our mathematical models enable us to predict daily water requirements. However, we still don't know if these estimates are valid or whether fluid intake matches the predicted requirement. Historically, researchers studying fluid intake in field training settings have had to rely on canteen exchange to look at individual soldier fluid intake. This can lead to error as soldiers may modify their drinking behavior when they know their intake is being monitored. A new type of canteen system available now may help address whether actual fluid intake matches predicted requirements and to carefully study factors that influence drinking behavior. This system consists of a collapsible bladder, a drinking tube and mouthpiece.

We have taken a commercial bladder type canteen with drink tube, and instrumented the drink tube with a flow meter. The output of the flow meter is sent to a microprocessor and stored for later processing. We call the system the Drink-O-Meter, and from it, it is possible to record when someone takes a drink, the volume they consume each drink, and the cumulative total consumed.

The Drink-O-Meter produces very linear and valid results when the drink velocity exceeds 9 ml per second (Figure 5, Left). To assess the accuracy of the device for measuring fluid consumption, seven trials were performed in which participants drank ad libitum from the instrumented canteen for several hours. Figure 5 (right) presents the difference between the volume recorded by the Drink-O-Meter and the actual volume consumed. The Drink-O-Meter differed from the actual volume by 16±26 ml (1.6±2.6%). Therefore, the device can accurately measure ad libitum fluid consumption. Furthermore, the flow properties of the flowmeter are appear adequate for measuring human drinking behavior as only 1 of 7 trials resulted in underprediction of fluid consumption.

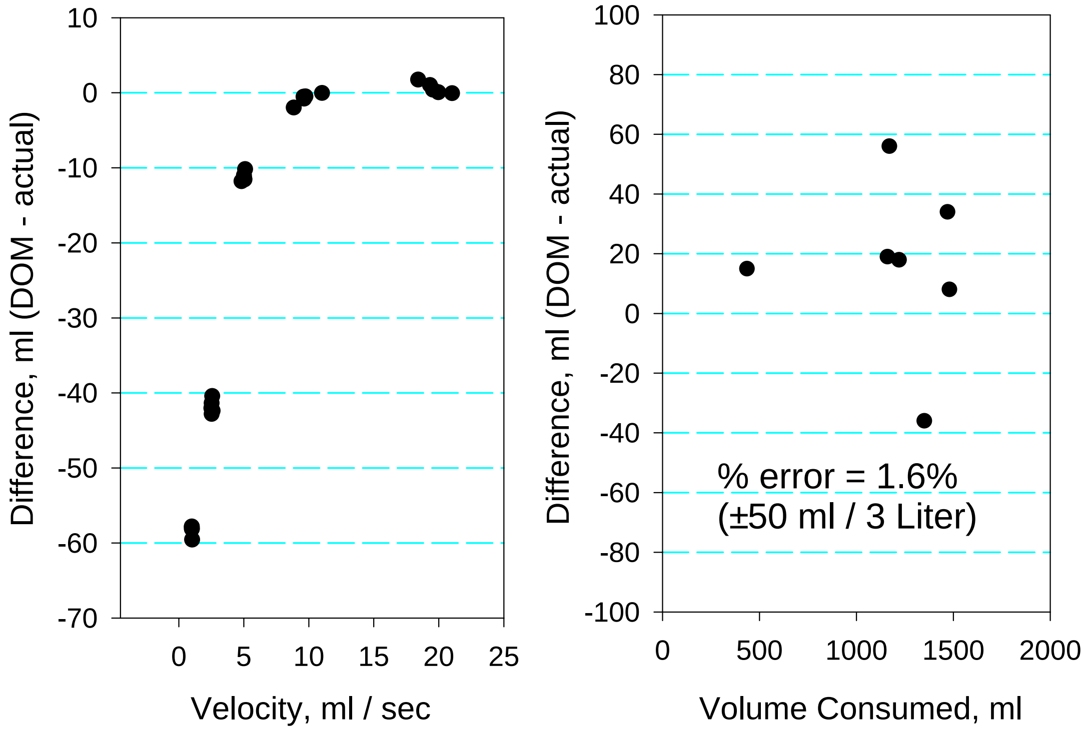

Figure 5. (Left) Accuracy of the Drink-O-Meter (DOM) system when known volumes of water were drawn through the drinking tube over a range of velocities. (Right) Accuracy of Drink-O-Meter for measuring ad libitum water consumption during work.

This system allows measurement of fluid intake in a very unobtrusive way over prolonged time periods. Figure 6 illustrates the cumulative water intake (top) and the volume consumed each minute (bottom) for a single individual performing prolonged work over a 55 hour period. The Drink-O-Meter data reveal that the soldier drank approximately 14 liters during the period with minute volumes ranging from 10 ml up to 170 ml and greatest intakes occurred during 3 time periods (0-10 h, 20-30 h, and 40-50 h). Thus, this type of system enables us to look not only at how much was consumed but when the fluid was consumed in relation to work, rest, etc. While the minute intake volumes might suggest that the soldier was drinking at very slow velocities, the plotted data are the total intake each minute and not the velocity of the individual drink. We are currently using the system to address whether actual fluid intakes match predicted fluid requirements.

Summary

The U.S. military has become sensitive that overhydration can compromise health and has acted to better sustain hydration during training. One action has been to revise fluid consumption guidelines used in training. This action appears to be having the desired effect. We are also developing new technology to study fluid intake in field environments. We foresee that this effort will help refine predictions of fluid requirements during combat situations and better sustain hydration.

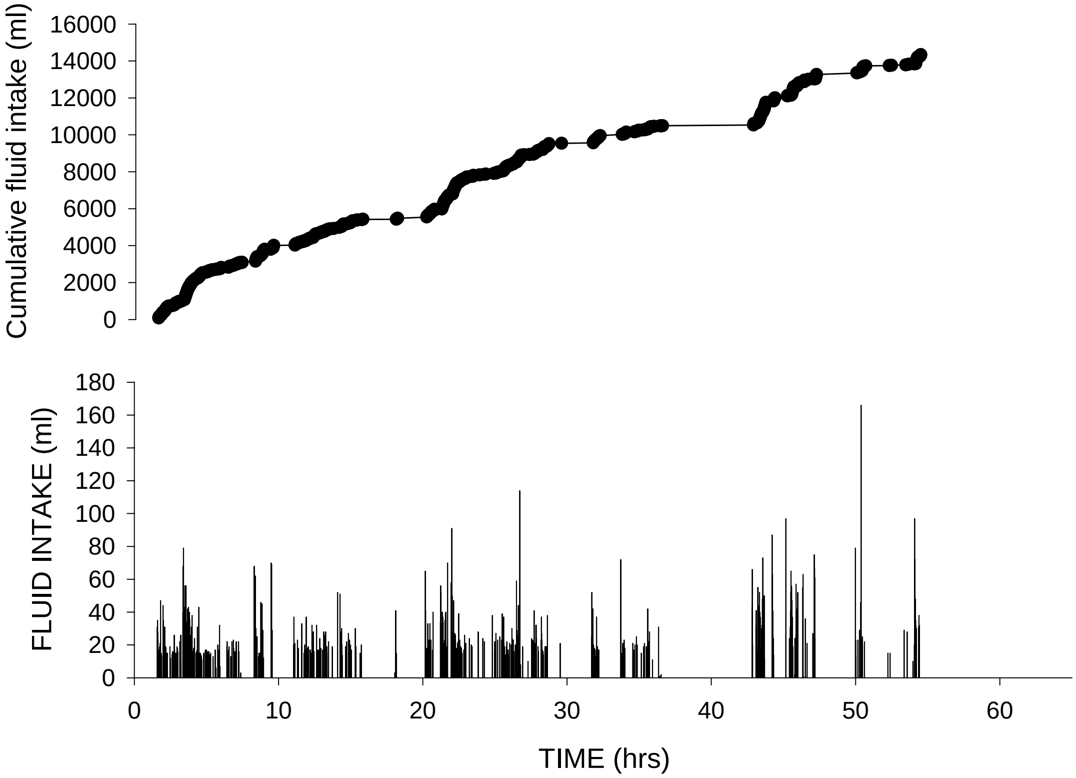

Figure 6. (Top) Cumulative water consumption of a single soldier during 55 h of sustained work. (Bottom) Fluid intake each minute of the 55 h task.

Acknowledgements

The authors thank the volunteers for their participation in the studies cited and the help provided by J. Brundage, W. Corr, S. Craig, C.M. Kesick , J. Knapik, M.A Kolka, J. Lanza, K.K. O'Brien, and J.E. Staab to help sustain the hydration of the warfighter. The views, opinions and/or findings in this report are those of the authors and should not be construed as official Department of the Army position, policy, or decision unless so designated by other official designation. Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USMRDC Regulation 70-25 on Use of Volunteers in Research. Approved for public release; distribution unlimited.

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Heuristic Modeling of Thermoregulation: Basic Considerations, Potential and Limitations

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Modeling of complex physiological phenomena has been attempted extensively over the years. The principal objective of modeling is to facilitate parametric presentation of the modeled phenomena. Ancillary objectives include the development of predictive capabilities, simulation of responses to environmental extremes not readily permissible under experimental conditions, etc.

Modeling can be categorized as follows:

(One) Regression modeling based on statistical techniques.
(Two) Heuristic modeling based on first principles, e.g., the first Law of Thermodynamics.

Regression modeling requires the *a priori* availability of large experimental databases. The data are analyzed for "best fit" options and statistical regression techniques are next employed to obtain the numerical values of the various parameters. Typical equational forms, widely found in the literature, include linear, polynomial, exponential, trigonometric and combinations thereof. In most cases regression parameters and levels of confidence of the model are also presented.

The main advantage of such models derives from their simplicity. They provide a convenient means for using relatively simple and straightforward equations for presenting large databases in assessing the relationship between physiologic variables and environmental parameters. The predictive power of these models is limited in the majority of cases, however, to the range of values for which the experimental databases were obtained. Thus, extrapolation beyond the original experimental range, although mathematically possible, may yield physiologically invalid values. Additionally, these models are usually "steady-state" ones, lacking time-dependent properties. While this is acceptable in a variety of cases, it may present a serious hindrance in other.

Heuristic modeling is very different in that it attempts to derive, rather than regress, the relationship between physiologic variables and environmental parameters from the mathematical expressions of natural laws. The underlying assumption is that natural phenomena are governed by certain laws. While these laws may be complex they are, nevertheless, amenable to relatively simple mathematical representation. For instance, the first Law of Thermodynamics (also referred to as the law of conservation of energy) may be expressed by an equation combining variables such as temperature, tissue physical and geometric properties, metabolic heat production, blood perfusion and time. These variables are cast into a differential equation for which boundary and initial conditions are specified. Once a solution to this equation, analytic or numeric, is obtained the predictions of the model need to be verified against experimental data.

This methodology has the potential of providing a powerful tool for describing and studying the responses of the thermoregulatory system under a variety of conditions and as a function of time. There are, in principle, no limitations on the range of parametric values for which the simulation applies but care must be exercised when analyzing the results.

In this lecture examples to the two types of models will be presented. Prediction and simulation capabilities of both modeling types will be discussed as well as their limitations.

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO MP-076.

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Overseas Experimentation: Method, Review, Interest and Feedback to Improve New Concepts of Protective Clothing

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Summary

The NATO military forces could be engaged under NBC thread in various climatic conditions which could expose them to warm temperature. Under hot climate, the soldiers, particularly when they wear full IPE (MOPP4), have to face an important physical and thermal load which decreases their operational capacity. A multi disciplinary team under joint Army Staff had developed a complete technical laboratory and field testing process in order to evaluate both the burden provided by the NBC IPE and the lost of capacity of the unit in operation.

This process is based on laboratory testing of the main technical parameters of suits, the measure of lost of individual physiological capacity for human subjects on trade mill, the measure of lost of manual dexterity, the measure of lost of visual field and sighting, the measure of lost of voice transmission and understanding and on field testing on overseas sites conducted with skilled military units on typical operational scenarios.

On the field, tactical scenarios are based on fighting missions of platoon infantry (Land forces) and on air rescue and search mission (Air force). The main recorded parameters used to determine the global lost of operational capacity are the followings : capacity to perform the mission, compared time to complete a mission under both level of protection, hydration needs, and thermal storage. Additionally, elementary tasks and firing exercises are achieved in order to quantify the impact of NBC protective suits on current battlefield actions. Only the methodological aspects of this full measurement process linked to physical and temperature burden are described in the paper.

Actual field trials under extreme climatic conditions are complementary with laboratory tests in order to get a concrete and realistic evaluation of the loss of operational capacity of military units that could be engaged overseas under NBC thread.

Introduction

The Nato military forces could be engaged under NBC thread in extremely warm climatic conditions. In this case the soldiers, particularly when they wear full IPE (MOPP4), have to face an important physical and thermal load that decreases their operational capacity.

A multi disciplinary team under joint Army Staff, (ie the medical service CRSSA, the technical section of the Army STAT and the main board armament DGA/CEB) has developed a complete technical laboratory and field testing process in order to evaluate both the burden provided by the NBC IPE and the loss of capacity of the unit in operation. These trials are fully integrated in a complete gradual and increasing program.

Only the methodological aspects of this full measurement process linked to physiological and temperature burden are described in the paper.

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

Method

This process is based on laboratory and field experiment :

- laboratory testing of technical parameters of suits, the main of them are the following ones :
  - isolation factor of suits using a instrumented thermal manikin,
  - air permeability and water porosity,
  - protection factor against toxic.

- laboratory testing of physiological parameters on voluntary subjects :
  - the loss of individual physical capacity of human subjects on trade mill,
  - the increase of skin, core temperatures and thermal storage,
  - the loss of manual dexterity and sensitivity,
  - the loss of visual field and sighting,
  - the loss of voice transmission and understanding,

The aim of this evaluation method is to compare the assigned task with the realised one, performed by the subject in different situations. For the NBC matter, we are used to compare a situation considered as a reference or blank (MOPP 0, battle dress) with the situation in full IPE (MOPP 4).

Required data

* Assigned task --> maximum score (Max Sc)
--> time :

It could be :
T ref }
- the necessary duration to perform the task,
- a reference time defined and imposed by the expert,

* Realised task --> score achieved by the subject,

--> time achieved by the subject to perform the task,

Abbreviation

Score achieved by the subject	: Sc subject
Time	: T subject

Definition of performance parameters

*** Quality coefficient Cq**

This coefficient expresses the quality of the realised task compared with the assigned task.

$$Cq = \frac{\text{Sc subject}}{\text{Max Sc}}$$

In the case of a multiple or complex task, depending upon several coefficients, we quantify, as far as possible, each of them separately and then we multiply all those elementary coefficients.

*** Efficiency coefficient Ceff**

This coefficient introduces the time factor in the realisation of tasks.

$$Ceff = \frac{Cq \times Tref}{T\ subj}$$

- If Cq = 1, it is not possible to quantify the score so :

$$Ceff = \frac{Tref}{T\ subj}$$

- If the task execution time is imposed, so

Ceff = Cq

NB : - during the execution of a task included a range of elementary acts, the training and the familiarization will conduct to an increase of the quality and efficiency coefficients. After this step, the low dispersion of these coefficients around an average result indicates accommodation of the subject. Them the tiredness begins and is linked with a gradual decrease of these same coefficients.
- In the case of an intensification of the task, linked with an excess workload of the subject, this will often conduct to a failure in the evolution of these coefficients.

Comparison of two situations

By using the performances coefficients of the subject in two different levels (MOPPO, MOPP4), it will be possible to compute the performance degradation and the operational efficiency loss.

*** Degradation rate Td**

It is calculated by using the two quality coefficients measured in the execution of the task in two different situations (full protection and battle dress).

$$Td = \frac{(1 - Cq\ IPE)}{Cq\ Ref} \times 100$$

*** Efficiency loss Leff**

It is computed by using the two efficiency coefficients measured in the execution of the task in two different situations (full protection and battle dress). It takes into account the modification of the execution time of the task.

$$L\ eff = \frac{(1 - Ceff\ IPE)}{Ceff\ Ref} \times 100$$

NB : - If some of these results are more than 100 %, it generally indicates a training or a familiarization of the subject.
- In some particular case, these results can be linked with particular tasks where the full protection does not affect the speed or the quality of the task execution.
- Moreover, the full protection can induce the subjects to differently perform the task than in battle dress or than included in the trial protocol.

Field trial review

The purpose of this kind of investigation is to evaluate in a hot country the effects and security limits of the wearing of different light NBC protective combat suits during various physical activities. Many field trials have been performed in Djibouti and French Guyana to study the activity of protected infantry soldiers.

- Moisture and very hot desertic climate (Djibouti)

1987: Feasibility study on field and checking out of the monitoring quality to ensure safety
1990: 1st overseas qualification on the field of the French NBC combat clothing (TOM).
1993: Comparative study of NBC clothing, influence of sweat on the protection efficiency.
Long-lasting stays in the desert (36 hours). 1st studies of dehydration effects.
1997 : Definition and use of reference scenarios, validation of a method to quantify the performances of an infantry fighting group.

- Hot and highly moist tropical climate

1998 : Evaluation of protective equipment in collaboration with DMO-DSO (Singapore)
1999 : Measurement of the efficiency of an infantry motorised platoon through 4 different scenarios (French Guyana).

Field testing on overseas sites are conducted with skilled military units on typical operational scenarios. On the field, tactical scenarios are based on platoon infantry fighting missions (Land forces) and on air rescue and search mission (Air force).

The main recorded parameters used to determine the loss of operational capacity are the following ones :
- capacity to perform the mission with residual capabilities,
- compared time between the same mission fulfilled in both level of protection,
- hydration needs which influence the maximal duration of mission and logistic supports,
- thermal storage which undermine the physiological limits of personal.

Additionally, elementary tasks and firing exercises are achieved in order to quantify the impact of NBC protective suits on current battlefield actions using the same computing method.

Local meteorology measurements

Records of micro-climate (Bruel & Kjaer device) are performed during all trials, as close to action as possible. They show the existence of the great variability during the day :
- the dry and wet temperatures of air,
- the humidity, linked to the solar load,
- the radiant charge depending on the position of the sun in relation to the horizon and the reflective nature of the ground, temporary modified by the possible presence of clouds,
- the wind speed,
- the possible temporary or long-lasting rains.

Physiological monitoring and safety

The same safety limits have been used in laboratory and during field trials (Fcmax 180 bpm, Tre 38.5°C) without any incident. However this type of exercise needs a real time monitoring of heart frequency (ie Polar system) and body temperatures (HTM 8000 data logger) of all voluntary people.

Interest and feedback

This test allows to know the real limitations of the wearing of protective NBC equipment in realistic conditions close to the battlefield and with variable climatic conditions. It also allows to know the loss of performances of typical combat group using protective equipment.

On the field, we measure real safety limits by wearing the whole NBC protective equipment. Moreover we notify and appreciate problems linked to the comprehension of communication, the dehydration, the vision, the manual dexterity (4, 5) and those linked to the mobility. In these conditions, rehydration is fundamental (6, 7) but the gas mask constitutes a potential constraint for drinking.

CONCLUSION

Actual field trials under extreme climatic conditions are complementary to laboratory tests in order to get a concrete and realistic evaluation of the loss of operational capacity of military units that could be engaged overseas under NBC threat.

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Accumulation of Sweat in Clothing During Interval Exercise in Cold Environment

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Summary

In cold environment (-15 ^{o}C, air velocity 2.5 m/s) interval exercise with exercise/rest periods of 30/30 minutes caused greater accumulation of sweat into clothing during a 120 minutes exercise/rest protocol as compared to 10/10 minutes exercise/rest protocol. The amount of sweating, body temperature and physiological strain were comparable in the two protocols. These findings suggest that the evaporation of sweat from clothing during prolonged interval exercise in cold environment can be an important factor affecting thermal protection.

Introduction

In cold environment accumulation of sweat into clothing can compromise its thermal insulation (1). In normal conditions clothing is reduced during the working phases and increased when resting. During military exercise the phases of physical work and rest can change so rapidly that it is not possible to adjust the amount of clothing. This can lead to excessive sweating during the working phases followed by excessive body cooling during the pauses in physical work.
The aim of this study was to find out if the duration of exercise/rest periods affect the accumulation of sweat into clothing during interval exercise in cold environment with pauses spent in warm environment.

Methods

The exercise/rest periods were either 10/10 minutes or 30/30 minutes, and the total duration of the protocol was 120 min. The subjects participated in the two protocols in random order and the experiment sessions were separated at least by three days. Exercise (walking 6 km/h on treadmill, slope 2 ^{o}) was performed in cold environment (-15 ^{o}C, air velocity 2.5 m/s). The resting periods were spent sitting at +10 ^{o}C, air velocity 0.2 m/s, with the same clothing as during exercise.

The subjects were 7 voluntary healthy young men. Their basic characteristics are shown in Table 1. Before entering this study their physical work capacity was determined by measuring the maximal oxygen uptake on treadmill. They were wearing Finnish military winter clothing (M91, thermal insulation about 2 clo) and rucksack (12 kg). During the rest periods drinking of water was allowed *ad libitum*.

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Table 1.
Basic characteristics of study subjects.

Subject	Age years	Height cm	Weight kg	VO_2max ml/kg/min
1.	24	179	62	59
2.	23	175	69	53
3.	23	182	66	60
4.	20	183	68	54
5.	29	178	87	44
6.	28	183	97	40
7.	24	183	71	52
Mean	24.4	180.4	74.1	51.7
SE	1.2	1.2	4.8	2.8

VO_2max = maximal oxygen uptake
SE = standard error of mean

Skin and deep body temperature were measured continuously (YSI 400-series thermistors and Squirrel 1200, Grant, UK) and heart rate was registered (Sport Tester, Polar Electro, Finland) during the whole protocol. Oxygen consumption was measured for five minutes during the last exercise period (Medikro 901, Medikro Oy, Finland). The amount of ingested fluid was measured. The subjects were weighted (Mettler ID1, Germany) without clothing before and after the protocol. The amount of sweating was calculated as the reduction in weight during the protocol added by fluid intake and reduced with metabolic weight loss. Clothing was weighted before and immediately after the exercise protocol and the accumulation of sweat into clothing was calculated as the increase in its weight. Data are given as mean ± SE. Paired T-test was used to compare the 10/10 and 30/30 minutes protocols. The study was approved by the Ethics Committee of the Institute of Occupational Health.

Results

The amount of sweating was comparable during the 10/10 protocol and the 30/30 protocol. The accumulation of sweat into clothing was lower ($p< 0.05$) after the 10/10 protocol than after the 30/30 protocol (Table 2). The fluid intake was greater ($p= 0.01$) during the 10/10 protocol than during the 30/30 protocol. The mean skin temperature, deep body temperature, mean body temperature as well as forehead and cheek temperature were comparable during the 10/10 and 30/30 protocols (Table 3).

At the end of the last exercise period oxygen consumption was 33.5 ± 0.9 ml/min/kg in the 10/10 protocol and 32.4 ± 3.8 ml/min/kg in the 30/30 protocol (ns). During the exercise periods heart rate was in average 150 beats/min in both protocols.

Table 2.
Sweating, accumulation of sweat into clothing and fluid ingestion during 10/10 and 30/30 minutes interval exercise protocols.

	10/10 min	30/30 min	p
Sweating (g)	809 ± 118	777 ± 81	ns
Accumulation of sweat into clothing (g)	353 ± 28	392 ± 32	0.018
Fluid ingested (ml)	457 ± 121	141 ± 41	0.010

mean ± SE, ns = not significant

Table 3.
Body temperatures during 10/10 and 30/30 minutes interval exercise protocols.

Temperature	10/10 min	30/30 min	p
Mean skin (^{o}C)	31.7 ± 0.2	31.3 ± 0.3	ns
Deep body (^{o}C)	37.5 ± 0.1	37.5 ± 0.1	ns
Mean body (^{o}C)	35.5 ± 0.1	35.4 ± 0.1	ns
Forehead (^{o}C)	27.6 ± 1.6	29.8 ± 0.7	ns
Cheek (^{o}C)	21.8 ± 1.4	22.1 ± 0.9	ns

mean ± SE, ns = not significant

Discussion

Physical work in cold environment requires clothing that is a compromise between sufficient thermal protection and body cooling. Normally in cold conditions an exercising subject reduces clothing and adjusts the pace of work in order to avoid excessive sweating. During resting periods additional clothing is added to guarantee thermal comfort. However, during military exercise the changes between physical work and rest can be so rapid and unpredictable that any adjustment of clothing is impossible. Moreover, military clothing has also other protective purposes than thermal protection. In that kind of situation thermal protection is often preferred leading to the fact that the thermal insulation of clothing is excessive during the exercise phases. This is followed by excessive sweating compromising the thermal insulation.

In the present study our aim was to find out if there are differences in sweating and accumulation of sweat into clothing during different types of interval exercise in cold environment. The observed differences can help to recognize and quantify the sweat accumulation problem as well as point out the characteristics of clothing which need further development. Our subjects had clothing with thermal insulation of about 2 clo. That is clearly greater than the calculated need of thermal insulation in our study conditions, which is 0.8 clo during the exercise phases and 1.6 clo during resting periods (ISO/TR 11079).

We compared the 10/10 minutes exercise/rest protocol to the 30/30 minutes exercise/rest protocol, both lasting for 120 minutes. It is evident that physiological strain was comparable in both protocols. The fluid intake was greater during the 10/10 protocol. Possibly the greater number of resting periods during the 10/10 protocol gave better opportunity for fluid ingestion which was allowed *ad libitum*. However, the amount of sweating was not significantly different in the two protocols. Thus it seems that the lower fluid intake during the 30/30 protocol did not lead to such hypohydration that would have reduced sweating (2-4). The accumulation of sweat into clothing was significantly greater during the 30/30 protocol. This seems to result from reduced evaporation during the 30/30 protocol, because there was no significant difference in sweating. The total durations of cold (exercise) and warm (rest) periods were similar in the two protocols. However, the longer continuous period in cold (30 minutes) could have lead to condensation of sweat into the clothing reducing the capacity of evaporation. In conclusion, our findings suggest that the evaporative function of clothing can become an important factor affecting thermal protection during prolonged interval exercise in cold conditions.

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Predicting the Risk of Freezing the Skin

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Summary
It is well known that wind increases the risk of frostbite during exposure in a cold climate. The explanation is that increased airspeeds enhance heat transfer from the body. This effect was quantified by Siple and Passel in the 1940s (14). They measured the time needed for water, inside a cylinder, to freeze during exposure to various combinations of air speed and temperature. From these data, they developed the so-called windchill index (WCI) for predicting the heat transfer from nude body parts. Later WCI was also expressed as "equivalent temperature" (T_e). However, a reexamination of the Siple and Passel data has shown that WCI (and T_e) does not correctly describe the wind induced heat transfer (5). As charts based on WCI and T_e are frequently used to express cold weather severity these indices should be corrected. Another shortage is that important parameters for predicting windchill are limited to air speed and temperature. A previously presented skin-frostbite risk model (5) has been developed further, now also allowing simulation of wet skin and solar radiation. The model suggests that the risk for finger frostbite increases from 30 to 70 % after wetting the skin when the air speed and temperature is 6,8 m/s and -15°C, respectively. This prediction is similar to experimental results found in the literature. There is a common opinion that windchill skin injuries are rare in the Antarctic during the summer. It is estimated that solar radiation corresponds to 5 to 10 °C higher air temperature. These values are much the same as those suggested by the model at solar intensities common during the Antarctic summer. Another opinion is that time spent in cold weather regions reduces the risk of skin frostbite considerably. This adaptation has been found to reduce the risk of finger frostbite from 74% (1st year men) to 29% (2nd year men). Such adaptation means that twice as high air speed or 2 - 5 °C lower air temperature is allowed at unchanged risk of skin injury according to the model. Risk model predictions have also been compared with cold weather injuries among U.S. soldiers in Alaska. It was found that the equivalent temperatures (T_e) that where associated with the greatest change in cold weather injuries coincided fairly well with increased risk of frostbite according to the model whereas commonly used T_e-windchill chart seems to underestimate the risk.

Introduction
Low air temperatures and high wind speeds are associated with an increased risk of skin freezing. Such injuries may result in extensive loss of duty-time and can also require long medical treatment. Hence, tools for predicting the risk of skin frostbite is valuable in order to reduce cold weather casualties. Siple and Passel (1945) exposed bare skin to different climates and observed at what combinations of air speed and temperature skin freezing occurred. In addition, they performed cooling experiments on a water-filled cylinder from which they derived their windchill index (WCI).

$$WCI = 1{,}162 \cdot (10{,}45 + 10 \cdot v^{0,5} - v) \cdot (33 - T_a) \qquad (W/m^2)$$

where v is the air speed (m/s) and T_a (°C) is the ambient temperature.

They reported that an increased risk of frostbite was prevalent at a WCI above 1400 ($kcal \cdot m^{-2} \cdot h^{-1}$). Finger frostbite at considerably lower WCI values than 1400 has also been reported. These exposures were, however associated with snow in the air or wet skin. Another factor of importance is presence of solar radiation and time spent in cold weather regions.

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The use of the windchill index has been widely spread, but its foundations and interpretation have been questioned from time to time. Surveys conducted in Canada (11) showed that the knowledge of windchill differed considerably between regions and between groups of people. Generally, a windchill index expressed as equivalent temperature (T_e) was preferred before e.g. heat flux-value expressed in W/m^2 or a WCI without a unit. Yet, it was emphasised that informing the general public is a major challenge as windchill indices often are presented in units that are not understood or in units causing confusion (11).

Different types of "Equivalent temperature" (T_e) have been derived based on slightly different conditions (11).

$$T_e = 33 - WCI / [1{,}162 \cdot (10{,}45 + 10 \cdot v_{ref}^{0{,}5} - v_{ref})] \qquad (°C)$$

where WCI is the windchill and v_{ref} is the reference air speed (often 1,7 or 2,2 m/s). The most commonly used T_e originates from the WCI of Siple and Passel (14) where T_e is calculated using a "reference air speed", often 6 or 8 km/h. This apparently small difference give rise to a 5°C difference in T_e, a difference that may cause a significant change in cold stress. If T_e is used only as an indication of thermal load this can be accepted. But the T_e - charts are often marked with risk zones informing of " Little risk", "Increasing risk" and "Great risk", zones where a 5°C difference can mean safe exposure time ranging from hours to 1 minute. An individual or a military commander preparing for cold weather activities would probably prefer a more informative risk chart, also including other risk factors relevant for windchill skin injuries.

Although both the WCI and related T_e are popular and frequently used these hold some disadvantages. One of them is that the heat transfer coefficient is incorrect not taking consideration in the air speed contribution at higher wind. Other drawbacks are that WCI have no base in human physiology or body parts dimensions. Nor is WCI suitable for predictions including additional parameters such as solar radiation, wet skin, acclimation e.t.c. Until now e.g. the effect of solar radiation is taken into account by introducing a correction factor in the form of adding a T_e-value. However, such a procedure is not, in principle, advisable because it tends to hide the mechanisms involved.

Therefore, the aim of this work was to improve a previously presented windchill model for prediction of the risk of skin frostbite (5) by including the effect of wet skin and solar radiation. The new model is based on general physical relationships describing the heat flux and temperature distribution from the skin to the environment. The physical model is linked to a risk model based on human data presented in the literature.

Heat transfer mechanisms

Skin temperature is mainly a result of two factors, heat loss rate to the environment and rate of heat input from the blood. A falling skin temperature can be counteracted if the physiological reaction CIVD (cold-induced vaso-dilation) opens the vessels so warm blood can reach the skin. The blood flow capacity in e.g. the fingers is so great that most windchill conditions can be compensated for if the CIVD can act in time. But, skin blood flow is impossible if the blood has frozen, a situation that happens at a blood temperature around -1°C (8). So, for a given CIVD reaction time the heat transfer rate from the skin decides whether the skin will freeze or not.

Convective dry cooling. Before the hunting reflex starts, the heat production and blood heat transfer to the skin are normally so low that the temperature change in the skin mainly depends on heat content of the actual body part and heat transfer rate from the skin to the environment. This physical process is driven by the temperature difference between the skin and the environment. The heat resistance of the skin, from the depth of the skin blood vessels outwards, is constituted by the insulation of cutis and epidermis. However, more important to the heat transfer rate is the insulation of the apparent still air layer surrounding the body part. The thickness of this layer depends on the air flow and surface characteristics. A textile layer or even a short beard improves the thickness considerably, thus reducing the heat loss from the skin. Concequently less skin blood flow is needed.

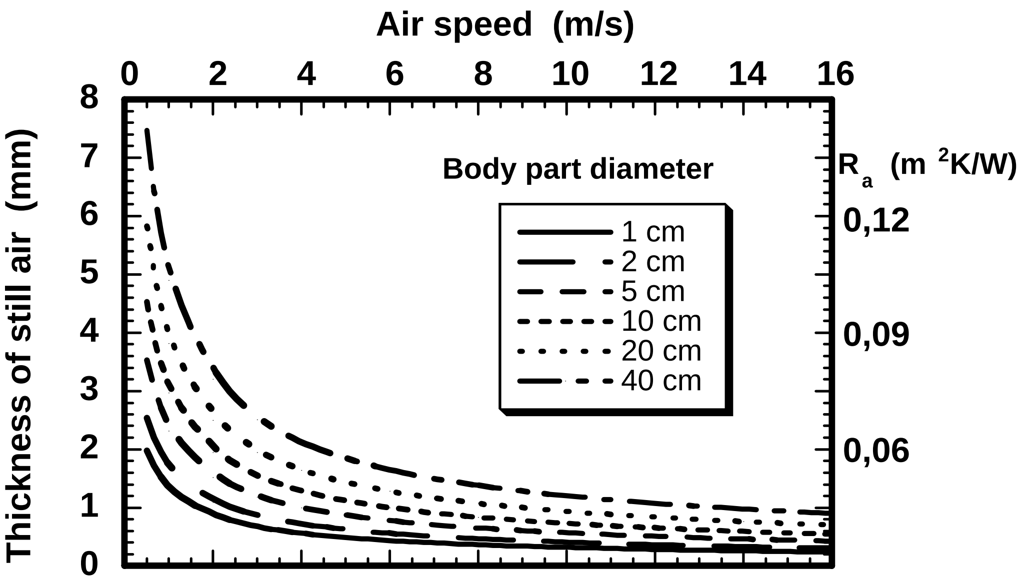

Figure 1. The thickness of the apparent still air layer (mm) surrounding an approximately circular body part in cross wind. The air layer is also given as insulation value (m^2K/W) including the radiation heat transfer coefficient.

The apparent still air layer thickness is calculated from the convective heat transfer coefficient (h_c) and it depends on a number of factors as body part dimension and shape, relative air speed and degree of external turbulence (fig. 1). If the wind flows across the body and the external air flow is approximately laminar the various body parts can be considered as cylinders of various shapes giving different heat transfer coefficients. The airflow characteristics around a circular cylinder depend strongly on the Reynolds number (Re) (no dimensions, ND).

$$Re = v \cdot d / \nu \qquad \text{(ND)}$$

where v is the air speed (m/s), d is the body part diameter (m) and ν is the kinematic viscosity (m^2/s). Hilpert (7) found that the average Nusselt number, Nu (ND), for a cylinder could be written as

$$Nu = h_c \cdot d / \lambda \qquad \text{(ND)}$$

where h_c ($W \cdot m^{-2} \cdot K^{-1}$) is the forced convection coefficient, λ ($W \cdot m^{-1} \cdot K^{-1}$) is the thermal conductivity of the surrounding medium and $Pr = \nu / \alpha$ is the Prandtl number (ND) where α is the thermal diffusivity (m^2/s).

Combining the equations above gives the general expression for h_c as

$$h_c = 4{,}47 \cdot d^{-0{,}38} \cdot v^{0{,}62} \qquad (W \cdot m^{-2} \cdot K^{-1})$$

for an air temperature of -25°C where the coefficient decreases from 4,47 to 4,37 at 0°C. The equation obtained by Danielsson (3) for a standing human, measured at +28°C was

$$h_c = 3{,}76 \cdot d^{-36} \cdot v^{0{,}61} \qquad (W \cdot m^{-2} \cdot K^{-1})$$

which is fairly similar to the correlation equation valid for cylinders in cross flow. The slightly lower coefficient for the human body depends somewhat on the higher temperature but mainly on the interference from adjacent body parts on the air streams (3). The formula displays the average h_c-value of the body part. If the heat transfer of a specific site is of interest the local h_c-value must be considered. It depends on the angle to the wind but is also affected by e.g. the interference from clothing items (4). The deviations around

the circumference of a body part can be fairly great compared with the average h_c-value (3). Undisturbed free air flow generally produce the greatest h_c-value on the windward side whereas the lowest values are found at right angle to the wind. On the leeward side there is another maximum but which is lower than on the windward side. For a part with approximately circular shape the h_c-value on the windward side is roughly 40% greater than the average value for all angles.

Even at strong winds the air layer, close to the body surface is approximately still. This layer constitutes a resistance against heat as well as mass transfer. Neglecting the long-wave radiation heat transfer at the skin surface, which is acceptable for slim body parts in "strong" winds, the thermal insulation value of the air layer, R_a, is calculated by inverting the h_c-value ($R_a = h_c^{-1}$). The result of such calculations, for different air speeds and body diameters, clearly shows that slim body parts are much more exposed to high cooling rates than wide ones. However, comparing these R_a-value with the insulation value of the cutis and epidermis, it becomes clear that the skin is of less importance than the air layer in protecting the deeper lying tissue. In the present model it is assumed that the thickness of the epidermis is 0,2 mm (normal range 0,1-0,7 mm) having a thermal conductivity of 0,21 $W \cdot m^{-1} \cdot K^{-1}$ whereas the cutis is set to be 1,5 mm thick (range 1-2 mm) with the conductivity 0,37 $W \cdot m^{-1} \cdot K^{-1}$ (6). Hence, the insulation value of the skin is approx. 0,006 m^2K/W. Even with a "thick skin" the air layer still dominates in respect of heat resistance. Nevertheless, the importance of the skin should not be underestimated as protection is a question of time until the hunting reflex is activated. So, even a small heat resistance value can reduce the temperature drop enough to make CIVD possible. Figure 1 clearly illustrates that great changes in air layer insulation occur at low air speeds whereas the relative effects are minor at strong winds. This explains why windchill charts normally don't cover air speeds greater than about 20 m/s. The shape of the R_a-curves also explains the importance of the reference air speed selected when calculating T_e. The two reference air speeds, 6 or 8 km/h (1,7 and 2,2 m/s respectively), normally used differ about 5°C in T_e, a difference that can be significant in terms of body cooling. So, the way of calculation is of importance when comparing T_e-values.

Evaporative cooling In the physical skin model heat is conducted through the skin components (cutis and epidermis). Various thermal properties of the skin are allowed by e.g. introducing water in epidermis. Water in epidermis can be combined with evaporation or not. Evaporation is assumed to take place at the skin surface and the rate of mass transfer depends on the ambient air layer thickness. Here, the skin is assumed to be uncovered but e.g. the effect of textile layer can be included. Under normal conditions when forced convection is valid, turbulent or not, the evaporative heat transfer can be estimated from Lewis relation, L, where

$$L = h_e / h_c = 16{,}7 \qquad \text{(K/kPa)}$$

where h_e ($W \cdot m^{-2} \cdot kPa^{-1}$) is the evaporative heat transfer coefficient. The apparent still air layer in terms of thickness, impeding the transportation of heat and mass, is approximately the same for heat, $d_{th} = 0{,}26 / h_c$ (m) as for mass, $d_e = 0{,}031 / h_e$ (m). The evaporative heat transfer is assumed to be forced by the water vapour pressure difference between the ambient air and the skin surface. The vapour pressure of the air is calculated from the temperature assuming a relative humidity (rh) of 80%. The partial pressure at the skin is based on rh = 100% and a skin temperature around 0°C.

Solar radiation. A balancing factor to the convective cooling of the skin is absorption of solar radiation. Such an input impedes the skin temperature drop or may even result in skin temperature rise. The solar heat input can vary considerably, from almost none to a net input reaching almost 1000 W/m^2. The short-wave radiation reaching the skin comes both directly and as reflection from the sky and the ground (albedo).

The direct radiation heat flux reaching the skin depends on the cloudiness, solar altitude and position of the exposed object. The sky- and in particular the ground albedo cause an heat inflow that is less dependant on angle between the incoming solar beam and the position of the object. This is because of the strong reflection if the ground is covered by fresh snow. For instance, if the face is turned away from the sun the direct solar radiation reaching the face is negligible whereas the radiation coming from the ground- and sky albedo can be of the same magnitude as the direct solar heat flux. When the sky is overcast, the albedo may become greater or much greater than the direct radiation because of multi-reflexion between the ground and the clouds (9). This situation demands, however, a very good reflectivity of the ground. If it is covered by fine,

fresh snow the reflectivity is very great, around 85%, whereas as comparison, a grass or soil surface reflection rarely exceeds 15-20% . The amount of solar radiation, absorbed by the nude skin depends slightly on e.g. the skin properties. The model assumes that 65% of the incoming short-wave radiation is absorbed whereas the long-wave emittance is set to 0,97. The radiation heat exchange occurs at the outermost layer of the skin both in case of absorption of short wave radiation or emittance of long-wave, thermal radiation. If there is a net inflow, the skin surface temperature rises, reducing the heat loss from deeper skin layers. The thermal effect of the solar radiation depends on the wind. At the same time as a higher skin temperature reduces the heat loss from deeper lying tissue, the heat loss outwards increases because of greater temperature difference. So, if the insulating air layer is thick, i.e. the air speed is low the effect of solar radiation becomes great. This is one reason why the clothing can be very light in Antarctic, in the summer. The temperature is rarely below -10°C, the wind is often light and there is a bright sunshine. However, if the wind is strong, reducing the air layer thickness, the advantage of sunshine becomes reduced as the absorbed heat is lost back to the environment to a higher degree.

Human windchill data

The physical model allows calculation of temperature gradients and heat fluxes if the boundary conditions are known. The model is not defined for specific heat transfer avenues. Hence, it could also be used for estimating the risk for burn injury. Irrespective of purpose, the model needs information on how the human body reacts on various climatic exposures. The technique used here, is to combine the physical model with the frostbite risk distribution associated with skin surface temperatures obtained from human studies.

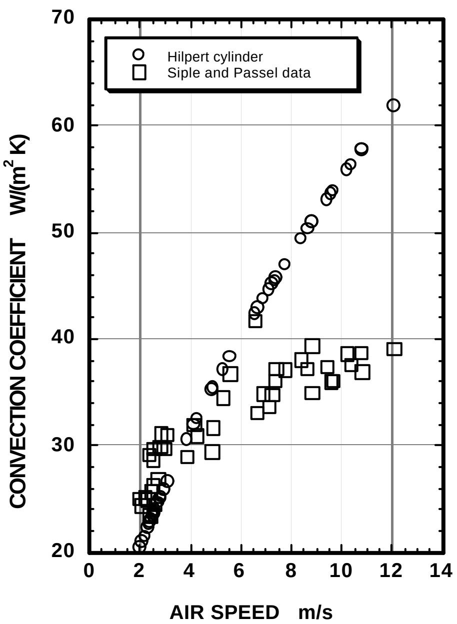

Figure 2. Comparison between convection coefficient suggested by Siple and Passel (14) and that normally obtained for a cylinder with the same diameter (6 cm) in cross flow (7).

Risk of frostbite. The Siple and Passel study (14) did not include human data, at first. Their experiments focused on the cooling rate of a water filled cylinder. They measured the time it took for the water to freeze for various combinations of air speed and temperature and from these data the cylinder heat flux-values (W/m^2) were calculated. However, the conversion from convective heat flux to "windchill factor" (convection heat transfer coefficient) included an error which still is present in all WCI and T_e -values. Siple and Passel did not account for the insulation of the cylinder wall. Consequently, their convection coefficient became incorrect and the relationship between wind speed and h_c differs from what is normal for cylinders in cross flow (figure 2). The consequence for the WCI and T_e-values is that these are based on a convection coefficient that is strongly underestimated, starting at air speeds exceeding 4-5 m/s (5).

Siple and Passel introduced the human aspect by exposing themselves and colleagues to different climates, noticing at which temperature and air speed frost nip occurred in the face. The corresponding windchill index was calculated from their windchill factor setting the skin temperature to 33°C. In spite of unphysiological skin temperature and a physically incorrect convection coefficient, yet Siple and Passel found that skin frostbite seldom occurred at windchill indices lower than 1400 ($kcal \cdot h^{-1} \cdot m^{-2}$). They also identified two other stages corresponding to WCI = 2000 and 2300. The "relative human comfort" for these three stages were verbalised as "Freezing of human skin begins, depending on activity, solar radiation, character of skin circulation. Travel and life in temporary shelter becomes disagreeable" (WCI=1400), "Conditions for travel and living in temporary shelter becomes dangerous. Exposed areas of face will freeze within less than one minute for the average individual" (WCI=2000) and "Exposed areas of face will freeze within less than half a minute for the average individual" (WCI=2300). These characterisations are still used in the widely spread WCI / T_e-tables.

Around 1970 Wilson and Goldman (16) conducted experiments on finger freezing in cold wind. They found almost no skin freezing at WCI values below 1400; values above this was often but not always associated with skin freezing. These data imply that a WCI of 1400 is a fairly good indicator of air speed and temperature that can cause nude skin freezing. However, they measured a considerable variation in the skin temperature when freezing occurred. Furthermore, their data on the freezing temperature of the skin differed considerably from those found by Keating and Cannon (8) who suggested a temperature around -1°C. Wilson and Goldman (16) and Wilson et al (17) found that the skin started to freeze at roughly -13°C and -9 °C respectively. However, according to Danielsson (5) these are some 3-4°C to low because of thermocouple error. Another discrepancy is that Keating and Cannon (8) measured the skin temperature from an intracutaneous track with the finger precooled to low temperature. In the other studies the temperature was measured on the skin surface with a thermocouple, with the assumption that a "true" skin temperature was obtained. This procedure, however, introduces the same type of error as that found in the Siple and Passel WCI-factor.

Based on the assumption that the skin between cutis and subcutis starts to freeze at -1°C, the physical model produced skin surface temperatures that were very close to those measured by Wilson and Goldman (16) after these had been corrected for the errors mentioned above. It was found that the skin surface temperatures were linearly related to the frequency of finger frostbite (5). The results (figure 3) suggest that the risk of finger frostbite for those individuals tested, increase linearly from 0 to 100% as the skin surface temperature drops from -4,6°C to -8°C. This relation has been used as "human" anchor in the physical skin model, together producing the windchill frostbite risk model. The extended model, now including evaporative cooling and solar radiation, is based on the same risk - skin surface temperature relation. The assumption has been that type of heat transfer avenue is not important to the occurrence of skin freezing, only what skin surface temperature that is reached.

From the cumulative distribution curve any combination of skin temperature and risk frequency can be obtained. In the risk nomogram the three risk levels 5, 50 and 95% with the related surface skin temperature -4,8°C, -6,3 °C and -7,8 °C respectively have been selected.

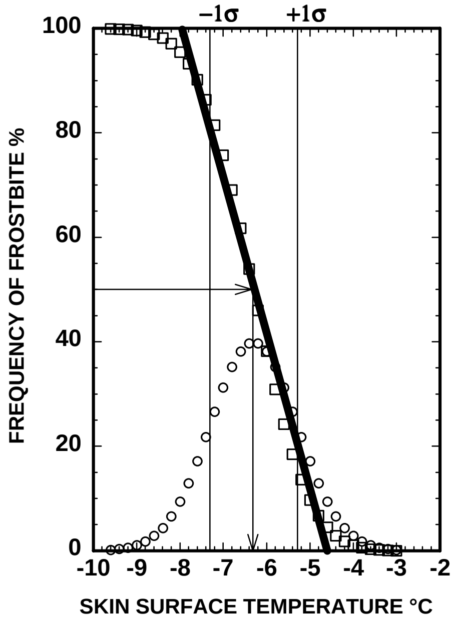

Figure 3. A standard normal distribution curve with a mean of –6,3 °C and SD (σ) of 1°C. Related cumulative distribution curve closely follows relation between calculated steady-state skin surface temperature and frequency of finger frost bite. –1 σ and +1 σ lines show skin surface temperature range where 68% of all frostbite cases can be expected for individuals who participated.

Fig. 4 shows what risk of frostbite a group of non-adapted people is exposed to for various combinations of air speed, air temperature, solar heat absorption on the skin when the skin is dry or wet. The risk curves derived for dry skin show a strong non-linear shape that basically mirrors the air layer thickness and its dependence on the air speed (c.f. fig. 1). At low air temperatures, around -30°C, an increase of air speed with roughly 1 m/s can be balanced by a 5°C rise in air temperature for the same frostbite risk. At -25°C a similar rise in temperature balances a 4 m/s increase in air speed and at -20°C the corresponding relation is 5°C versus around 12 m/s change in air speed. The risk curves for wet skin show similar shapes as the dry skin curves due to the close relationship between dry and evaporative heat loss (Lewis relation). The curves indicate that at air temperatures around -10°C or above, where the risk of freezing a dry skin is small, the risk becomes considerable great if the skin becomes wet. Bright sunshine combined with a high ground reflection value reduce the risk of skin freezing substantially. The solar radiation, absorbed by the skin can reach 1000 W/m^2 or more during the summer in Antarctic. At temperate latitudes, the corresponding absorption rate is considerably lower but 400-500 W/m^2 can probably be reached on a clear day if the ground is covered by fine, fresh snow.

Validation

It is difficult to validate the risk curves because of ethical reasons. The amount of experimental data except those used for the development of the risk curves are very limited. The empirical data from outdoor activities often lack of important information. The climatic situation is often given as time-averaged figures and the relative air speed is sometimes estimated by experience or obtained from the standard 10 m level, often at some distance from the location of exposure. Nevertheless there are some unused data or implications that can be used for validation of the risk curves.

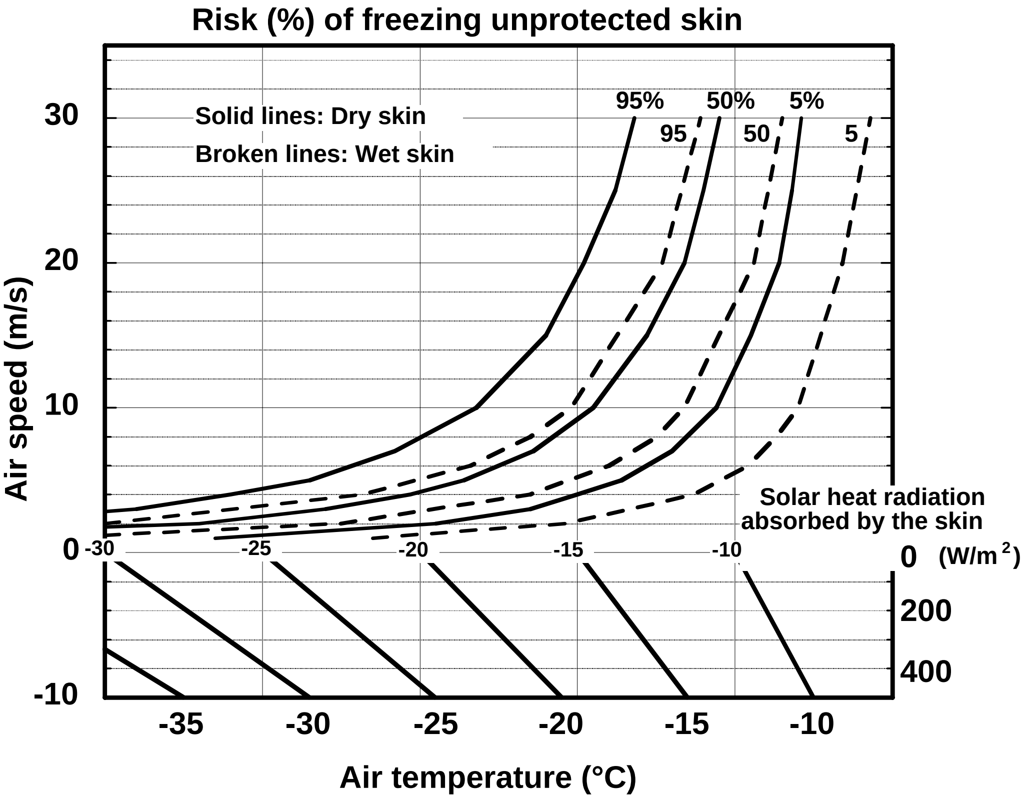

Figure 4. Risk of frostbite on windward side of a slim body part (diameter 2 cm) at various airspeeds, temperatures and solar heat absorbtion. Directions for use: From solar heat absorbtion go horizontally to air temperature. Then go vertically to air speed. Estimate risk of freezing the skin from solid curves in case of dry skin, else use broken curves (wet skin). Exemple: 200 W/m^2 of solar radiation absorbed by the skin and an air temperature of –15°C gives 50% risk of frostbite if the air speed is 13 m/s and the skin is dry. A wet skin increases the risk to approx. 90%.

Dry skin. Controlled experiments. Table 1 shows a comparison between predicted and observed frostbite frequencies from Wilson et al (17) and previously unpublished data of Wilson and Goldman (16). The data of Wilson et al (17) are given as average frostbite risks (45%) because the number of exposures under each climatic condition are not known.. There seems to be fairly good agreement between predicted and observed data, except with some of the previously unpublished data (16). The reason for this can be that experimental conditions (these are unknown) are not comparable with those on which the risk curves are based. A change from 0% to 63% observed frostbite frequency as a result of only 2°C lower temperature at 10 m/s (16) supports the suspicion that other factors have been involved. But it should also be kept in mind that the controlled experiments rarely involved more than 6 or 7 subjects. So, a "random" variation in number of frost-bitten subjects of one individual causes a 15-20% change in "frostbite risk".

*Table 1. Comparison between observed and predicted frostbite frequencies. * Average result; ** unknown experimental conditions.*

air temp/air speed (°C/m/s)	observed frostbite frequency (%)	predicted frostbite frequency (%)	reference
-15/6,8	45	35	Molnar et al. (13)
-15/6,8	45*	30	Wilson et al. (17)
-15/9	45*	50	Wilson et al. (17)
-15/10	45*	55	Wilson et al. (17)
-12/10	45*	20	Wilson et al. (17)
-13,5/10	80	35	Wilson and Goldman (16)**
-17,5/4,5	0	30	Wilson and Goldman (16)**
-11,5/10	63	15	Wilson and Goldman (16)**
-9,5/10	0	0	Wilson and Goldman (16)**
-14,5/6,5	46	30	Hughes (Wilson and Goldman)(16)**

Outdoor frostbite injuries. A five-year review of the risk of cold weather injuries among U.S. soldiers in Alaska (1) shows that almost 40% of the injuries were frost-bitten ears and noses. Slightly more than 50% of the injuries were related to the feet and hands. It is reasonable to believe that the frequency of the frost-bitten ears and noses should depend on the windchill whereas the hand and feet injuries probably could be more related to the temperature only. However, the study indicates that the accumulated frequency of cold weather injuries was well related to the equivalent temperature (T_e).

Chandler and Ivey (1) found that the greatest increase, from 30% to 80% of all injuries (accumulated causality frequency) occurred at the equivalent temperature range -30°C to -40°C. They also found that more than 70% of all injuries occurred below T_e = -29°C. The reference air speed 1,67 m/s was used for the T_e calculations. These results can, with some caution, be used for validation of the risk model. If the predictability of the nomogram is acceptable both for laboratory exposures as well as cold injuries in Alaska during very different environmental conditions including military activities, would make the nomogram fairly general. Table 2 shows the windchill chart (15) where the T_e-values are replaced by the risk value (assuming dry skin and no solar radiation) calculated for the same air speed and temperature. The marked cells in the chart correspond to the T_e-values ranging from -30°C to -40°C. The chart is stratified into three zones with ascending risk expressed as "Little danger" (upper left), "Increased danger" (middle) and "Great danger" (lower right). The table shows that the frostbite risk values, calculated for a slim body part (d = 2 cm) coincide fairly well with the marked cells showing when the accumulated frequency of cold weather injury increased from 30 to 80%. Taking consideration in that the accumulated frequency for a specific T_e slightly underestimates the actual risk frequency this could mean that the prediction value of the nomogram is still better than shown. The table also indicates that the risk zone classification "Little danger, Increased danger e.t.c. " seems to underestimate the risk as the change from 30 to 80% of all injuries occurred between "Little danger" and "Increased danger". The same comparison as in table 2 was done now assuming that the exposed body part was wider, with the diameter 15 cm as e.g. the head (Table 3). The table shows that risk predictions clearly underestimate the reported injury frequencies. The conclusion is that slim parts as nose, ears and fingers should be more exposed to injuries than wider parts as e.g. the face. This is confirmed by the reported data (1) as only 8% of the injuries were related to the face and other parts of the body.

Table 2. Windchill chart showing risk levels (%) for frostbite at various combinations of air temperature (°C) and air speed (m/s) assuming dry skin and no solar radiation.. The risk levels are taken from figure 4 and assume a slim body part as nose, ear, finger e.t.c. (diameter d = 2cm). The grey-marked cells denote T_e ranging from -30°C to -40°C (ref. air speed 1,67 m/s). The upper-left zone refers to "Little risk", the middle zone to "Increasing risk" and the lower-right one to "Great risk" (15).

v\Ta	-6,6	-12,2	-17,8	-23,3	-28,9	-34,4	-40	-45,6	-51
Calm	0	0	0	18	47	76	100	100	100
2,2	0	0	0	32	68	100	100	100	100
4,5	0	0	35	82	100	100	100	100	100
6,7	0	6	62	100	100	100	100	100	100
8,9	0	18	79	100	100	100	100	100	100
11,1	0	29	97	100	100	100	100	100	100
13,4	0	38	100	100	100	100	100	100	100
15,6	0	44	100	100	100	100	100	100	100
17,9	0	53	100	100	100	100	100	100	100

Table 2. Windchill chart showing risk levels (%) for frostbite at various combinations of air temperature (°C) and air speed (m/s) assuming dry skin and no solar radiation.. The risk levels are taken from figure 4 and assume a body part with a diameter of 15cm (the face e.g.). The grey-marked cells denote T_e ranging from -30°C to -40°C (ref. air speed 1,67 m/s). The upper-left zone refers to "Little risk", the middle zone to "Increasing risk" and the lower-right one to "Great risk" (15).

v\Ta	-6,6	-12,2	-17,8	-23,3	-28,9	-34,4	-40	-45,6	-51
Calm	0	0	0	0	0	0	12	29	44
2,2	0	0	0	0	0	6	26	44	62
4,5	0	0	0	0	24	47	74	100	100
6,7	0	0	0	18	50	79	100	100	100
8,9	0	0	0	35	71	100	100	100	100
11,1	0	0	12	50	88	100	100	100	100
13,4	0	0	21	62	100	100	100	100	100
15,6	0	0	29	74	100	100	100	100	100
17,9	0	0	38	85	100	100	100	100	100

Acclimation. Acclimation factor in terms of time stayed in cold regions has been reported to give fewer frostbite injuries. It is not clear whether the acclimation mirrors a more competent behaviour during cold exposure or if the reduced risk is an effect of well-documented physiological adaptation giving less susceptibility to frostbite. A guess is that both behaviour and physiology contribute to a lower risk. Massey (12) reported that during a controlled windchill exposure 74% of first year men on Antarctic developed frostbite whereas only 29% of the second year men. Candler and Ivey (1) also identified a higher risk for frostbite for the first year soldiers in Alaska, yet without reporting a more specific result. Applying the Massey-data to the risk nomogram, it suggests that people with more than one year of cold weather experience can endure twice as high air speed, or 2 - 5°C lower temperature, as newcomers can for the same risk of freezing the skin.

Wet skin. Controlled experiments and outdoor experience have indicated that wet skin increases the risk of frostbite. Frostbite at "low" WCI is often associated with when there is snow in the air because of snowfall or strong winds (snowdrift starts at air speeds greater than 8-9 m/s (10)). The process responsible for the increased risk have not, as far as this author knows, been investigated. However, if the heat loss is roughly constant, the skin surface temperature falls continuously (laboratory situation). Outdoors, it may vary depending on the boundary air layer thickness which in turn results from factors as physical activity, wind direction, precautions taken to break the wind e.t.c. During such dynamic situations it is possible that the surface skin temperature passes through the freezing point. If the snow melts on the skin an evaporation process starts increasing the rate of heat removal from the surface. According to Massey (12) "skin numbness" came up to a much greater extent when there was snow in the air compared with no snow. He found that at windchill of 800-1000, snowdrift increased the numbness frequency with a factor of two whereas the increase was six-fold at windchill between 1000 and 1200. Skin freezing does not necessarily follow skin numbness, but a greater numbness index indicates lower tissue temperature, probably due to a greater cooling rate. However, these data can not be used for validation of the wet skin risk curves. Molnar et al. (13) studied the effect of controlled skin wetting. They found that water in epidermis caused skin frostbite in 6 out of 7 subjects (86%) whereas with dry skin frostbite was developed in only 3 cases out of 7 (43%). These results were obtained at an air speed of 6,8 m/s and the temperature -15°C. The risk curves for wet skin suggest 70% risk of freezing the skin whereas dry skin should only cause frostbite in 30 % of those individuals exposed. This study was performed with the skin quickly wetted (less than 30 s), a procedure that prevents the skin to be soaked with water. The same study revealed that freezing took place at slightly higher skin temperature when the skin was wetted. This finding is consistent with the physical model as water in epidermis lowers the insulation value. Keeping the skin freezing temperature and ambient air temperature fixed the surface temperature must rise due to the water in epidermis as long as the outer air layer insulation is unchanged. These mechanisms and its effects on the temperature distribution and heat flux can be simulated. The present model shows that the contribution from a dry epidermis to the total thermal insulation is very low meaning that a wet skin should only give a small contribution to the risk of freezing the skin, provided evaporation is prevented.

Solar radiation. Solar radiation reduces the risk of skin frostbite. This has been stated several times in the literature, primarily by members of Antarctic expeditions (e.g. Siple and Passel (14)). From heat transfer theories it is highly reasonable that if the cooling rate is slowed down by e.g. heat input from an external source applied to the skin surface, the risk of frostbite should be reduced. Yet, this effect has not, as far as this author knows, been shown explicitly in controlled experiments. So, the risk nomogram can not be validated strictly in this sense. The statement can only be supported implicitly. Chrenko and Pugh (2) have thoroughly described the contribution of solar heat radiation to the human heat balance. Based on observations at Maudheim, Antarctic by Liljequist (9) they showed that the direct solar radiation, on a clear day, is around 750 W/m^2 at an solar altitude of 10° and about 1050 W/m^2 at an angle of 40°. More relevant for an individual performing normal outdoor activities is the intensities measured on a vertical surface, e.g. the face. There the corresponding figures are 175 and 750 W/m^2, respectively. Important is also the ground albedo when the it is covered by fine, fresh snow. The indirect radiation can be of the same magnitude as the direct one. Even when the sky is overcast the radiation can be up to 60% of the direct radiation on a clear day. This is because of the highly reflective snow producing multiple reflections between the ground and the clouds (in temperate latitudes this value rarely exceeds 25% (9)). So, the total radiation falling on a vertical surface, including sky albedo, is around 400 W/m^2 at the solar altitude 10° and as much as 1500 W/m^2 at 40°. Even with the face turned away from the sun the solar radiation is still about half these values. Assuming that the short-wave absorption of the skin is 65% the amount of heat absorbed by the skin ranges from about 150 W/m^2 at 10° solar altitude with no direct solar radiation to about 1000 W/m^2 at an altitude of 40° with direct radiation included. A rough guess is that these values should be reduce by 50% for temperate latitudes. In Antarctic, at -15°C and 9 m/s with no solar radiation the frostbite risk curves suggest about 50% risk of skin injury, a risk that is reduced to 5% if only indirect radiation reaches the body at an solar altitude of 40°. As this combination of air speed and temperature is rare during the Antarctic summer (18) skin frostbite should be uncommon. This is also in line with the experiences made. The effect of the solar radiation has also been expressed as equivalent rise in air temperature. Subjective opinions (e.g. 2) suggest that solar heat input may correspond to 5 to 10°C rise in air temperature. This is in line with the present model because the solar radiation intensities mentioned above correspond to a similar temperature range in the risk nomogram.

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Heat Stress Indices in the Hellenic Air Force (HAF)

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SUMMARY

Introduction: Greece is characterized by very hot weather during summer. Since 1987, Hellenic Air Force (HAF) has adopted the Discomfort Index (DI) as its official heat stress index (HSI), nowadays considered as outdated.

Rationale: Because of the disadvantages that DI presents, a study was performed in order to examine the possible application of another heat stress index, more objective and accurate in predicting heat discomfort.

Materials and methods: For two months the Wet Bulb Globe Temperature (WBGT) index was calculated inside a bubble canopy (F-4) and a rotary wing (C-130) aircraft (WBGTa) as well as their respective runway WBGT data (WBGT ground, WBGTg). The same set of data was used to calculate Fighter Index of Thermal Stress (FITS) for the same time period. Flight log of four different AF Bases were accessed in order to determine the possible cancellations of flights due to Indices of Thermal Stress, as calculated.

Results: For the bubble canopy aircraft, the WBGTa may be considered equivalent to WBGTg because the aircraft remain on ground stand-by with canopies open. FITS value of 38 was found to be statistically equivalent of DI 28.6. Both were compared to DI currently in use.. On this basis, the number of flight cancellations due to WBGTa was limited by 77%, and by 99% due to FITS, as compared to cancellations due to DI. For the rotary wing aircraft, WBGTa and WBGTg were found in statistically significant correlation (t-test, paired, $p<0.0001$), therefore the former index may be used to predict the later.

Conclusions: The Discomfort Index (DI) may be replaced in the HAF as follows: For ground personnel, by the WBGT Index of thermal stress. For flying personnel, by WBGT for moderate or light work. For aircrew of airborne bubble canopy aircraft FITS (extended range) may be applicable, after elaboration for Mediterranean climatic conditions.

INTRODUCTION

Due to very hot and dry summer that characterizes Mediterranean type of climatic conditions, application of an objective and accurate heat index is a matter of safety either for flying or ground personnel.

Environmental factors, which are accepted as parameters in calculating heat stress, are dry (air) bulb temperature, humidity, air velocity and radiation (solar and infrared). Since 1987, Hellenic Air Force (HAF) utilize Discomfort Index **(1)** (DI) as their official heat index given by:

$$\mathbf{DI = T - 0.4\,(T-10) \times (1 - F/100)}, \qquad \text{(Equation 1)}$$

Where: “T” presents ambient temperature and “F” relative humidity.

When DI is reached 27 there is a recommendation for all non-essential flights to be cancelled and outdoor work regarding maintenance to be discontinued.

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They are disadvantages associated to the use of DI by military personnel:

1. DI is useful to provide general public with advice regarding heat stress and not military personnel in specific.
2. DI at its present form does not account for effects of radiant heat, a crucial environmental factor either during flight or groundwork, leading to impairment of aircrew performance, which may be further impaired by the “greenhouse effect” phenomenon **(2)** it precipitates.

The operational requirement for a new Heat Stress Index (HSI) included the following:

1. Accommodation of environmental factors, such as wind velocity, humidity and radiant heat.
2. Ease of use by untrained personnel (automatic calculation, if possible), based on readily available data, which should be easily read and interpreted in operational terms.
3. Significant correlation between ground weather data and personnel working conditions..
4. Task specific, thus able to assign values for both ground personnel and aircrew.

Aircrew working conditions were further categorized according to aircraft type: bubble canopy aircraft (e.g. fighters, helicopters) and large haul aircraft (e.g. C-130, etc)

As a result, a study was performed in order to determine possible ways of applying heat stress indices for ground personnel and aircrew according to work profile and aircraft type

MATERIALS AND METHODS

The following Heat Stress Indices were selected (further selection details in Discussion):

1. For ground personnel, the Wet Bulb Globe Temperature Index (WBGT) as described by Yaglou (1957).
2. For aircrew, the Fighter Index of Thermal Stress (FITS), as defined by Nunneley, (1979).

Meteorological data were prospectively acquired in four different HAF bases (110, 111, 112, 114 HAFB), for a period of two months each, in order to calculate WBGT and FITS values. All data were recorded between 10.00hrs and 19.00hrs daily for two consecutive months. The total testing period lasted several months (June- September 2001).

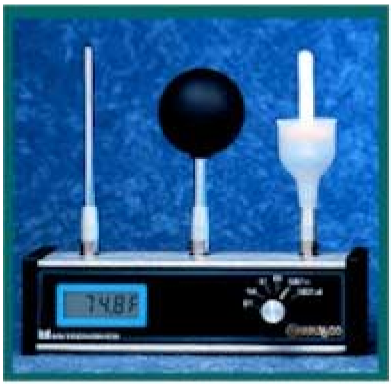

Figure 1: Heat Stress Monitor apparatus used (Metrosonic® HS 3600 heat stress monitor)

In particular, WBGT values were obtained automatically using a Metrosonics® HS 3600 Heat Stress Monitor equipped with a data logger. Two sets of devices were used simultaneously, the first based on ground (to serve as control data set) and the second inside an aircraft cockpit to enable correlation. The aircraft types included in the project were: McDonnel Douglas F-4, C-130 Hercules, Augusta Bell helicopter Type 205 and Super Puma.

Furthermore, meteorological data were pooled and flight logs of the same HAF bases were accessed and reviewed for period 1996- 2000 (all four years) in order to retrospectively calculate the WBGT and FITS values for the same bases at the respective time frame, and to determine their possible operational impact.

Because the regulations determine that whenever ambient temperature exceeds 30^{o}C the canopy of aircrafts with bubble canopy remains open. Bear this in mind, measurements were made in the F4 aircraft cockpit and at the runway, near the aircraft, using Metrosonics® heat stress monitor, so as to estimate the relationship between the existing heat stress in the open cockpit and at the runway.

The same measurements were made in the cockpit of C-130 aircraft and AB-205 helicopter, in order to calculate, if possible, similar to FITS index.

RESULTS

WBGT values for ground measurements (WBGTg) and for aircraft measurements (WBGTa) were reviewed and mean values and standard deviations were calculated.(Table II). Statistical analysis was carried out using paired samples T-test The mean difference between the WBGT ground (WBGTg) and WBGT aircraft (WBGTa) is –1,11790 (SD: ±4,3468). The mean WBGTg correlated to WBGTa ($p<0{,}001$).

WBGT	Mean (^{0}C)	N	SD	STE Mean
WBGTg	28,2549	268	3,7161	,2270
WBGTa	29,4339	268	3,6745	,2245

Table I: Mean and SD for WBGT aircraft (WBGTa) and WBGT ground (WBGTg) measurements.

Restrictions posed to work activities (including flight schedule) is summarized for DI, WBGT and FITS in Table 2, according to individual established gradients, respectively.

Classification	DI	FITS	WBGT	
			Values	Recommendation for Restriction
Caution	N/A	32-38	28-29.3	Ground operations (preflight and cockpit stand by) limited to 90 min maximum. A minimum of 2 hrs for post flight recovery maintained.
Danger	N/A	**38**-46	29.4 - 31	All low level flights (landing practice, close support missions) cancelled. Ground operations limited to 45 min or less.
Cancellation	**> 27**	> 46	> 31	Cancellation of all nonessential flights

Table 2: Heat stress operational significance according to DI, FITS and WBGT. For example, WBGT Recommendation for Restrictions applicable for each stage is introduced.

For 110 HAF Base specifically, the operational impact on flight schedule is presented in Table 3.

Heat Stress Index	Caution	Danger	Cancellation	Comment
DI	N/A	N/A	145	Previously used HSi
WBGT	40	11	8	Reduction by 95.5%
FITS	446	19	1	Reduction by 99.7%

Table 3: Operational impact on flight OPS as determined by recommended action for each HSi for a specific HAF Base (110 HAFB).

DISCUSSION

The selection of Wet Bulb Globe Temperature **(3)** (WBGT) was based on its best fit into the criteria shown in Introduction. Thus, ease of use combined to automatic calculation (Metrosonics Heat Stress Monitor), simplicity, cost-effectiveness, and accounting for humidity, wind effects, temperature, radiant heat, and work type.
This may be shown in the WBGT Index calculation formula:

$$\mathbf{WBGT = 0.7\ T_{wb} + 0.2\ T_{bg} + 0.1\ T_{db},} \qquad \text{(Equation 2)}$$

where: "T_{wb}" = natural wet bulb temperature, "T_{bg}"= 150mm black globe temperature, And "T_{db}"= dry bulb temperature

Furthermore, Harrison et al (1979) **(5)** have shown correlation between WBGTa and WBGTg for the temperature range 16-25 ^{0}C, which may be extendable to hotter environments **(6)**.
Our results confirm the correlation between WBGTa and WBGTg in an expanded temperature range (13-39 ^{o}C).
Therefore, WBGT may serve as a reliable HSI for ground personnel and aircrew involved with ground activities. Likewise, HAF have ordered canopies open in case environmental temperature exceeds 30 ^{o}C, when fighter aircraft remain in ground stand-by mode, thus WBGTg may be used as a HSI.

For the rest of the bubble canopy aircraft (helicopters and fighters with closed cockpits), FITS was considered for application. The Fighter Index of Thermal Stress (FITS) developed at the USAF School of Aerospace Medicine by Nunneley and Stribley (4) provides a realistic guideline for insuring safe fighter operations in hot weather. FITS may be calculated as follows:

$$\mathbf{FITS = 0.83\ T_{pwb} + 0.35\ T_{db} + 5.08,} \qquad \text{(Equation 3)}$$

where: "T_{pwb}" = psychometric wet bulb temperature, and "T_{db}"= dry bulb temperature, both measured at ground level in ^{o}C.

	FITS Range			DI
	Caution	**Danger**	**Cancellation**	**Cancellation**
110 HAFB	75	33	**1**	**35**
114 HAFB	72	24	**0**	**127**
116 HAFB	87	28	**0**	**107**
120 ATW	84	34	**0**	**101**

Table 4: Operational impact of heat Stress in four HAF bases, as recommended by DI and FITS HSIs, respectively. Numbers refer to cancellations for the period 1996-1999 inclusive. Actual number of flights classified.

FITS chart is partly based on data correlating cockpit conditions to WBGTg. Any FITS application is based on the simplifying assumption that (4):

1. On clear days (full sun) Tbg, exceeds Tdb by 10 ^{o}C on both ground and cockpit,
2. Aircrew are in lightweight clothing, and
3. Their metabolism is 2 to 3 fold the resting values.

FITS is primarily designed to provide operational supervisors with an easily used guide to predictor of cockpit environmental conditions during low-level missions which may jeopardize aircrew performance.

However, the number of cancellations of flights due to FITS calculated retrospectively for the period 1996-1999 inclusive, show considerable tolerance (Tables 3and 4) to extremes of heat recorded during the same time frame, with respect to the ones after DI or WBGT application.

There may be several reasons for this discrepancy: Although WBGT and FITS are based on the same data, FITS does not account for black globe temperature, which presents radiant heat, a crucial element of the Mediterranean type of climatic conditions (Equations 1-3). Instead, FITS is based on the assumption that WGBTg will be different from WBGTa by 10 ^{o}C at least, which was not confirmed during this study accommodating temperature extremes reaching 39 ^{o}C and recorded during fully sunny days (main WBGTa-g difference was found: –1,11790 (SD: ±4,3468)). Likewise, the impact of air humidity is very low, due to the extremely dry conditions of the Mediterranean summer.
Retrospective calculations of FITS and DI for the period 1996-1999 have also shown a FITS value of 38 ^{o}C (when FITS flight restrictions start to apply) to be equivalent of a DI value of 28, thus resulting in a much looser criterion than the previously used DI value for flight cancellations, whose value was set to 27. Therefore, some work may be necessary to improve applicability of FITS to Mediterranean climate, specially when more protective clothing are considered for aircrew, further diminishing the efficiency of body heat loss mechanisms such as NBC protective ensembles.

The main concern of bubble canopy aircraft pilots concern their ground stand-by phase about possible detrimental effects on their flying performance. For fighter aircraft, open canopies may provide significant relief, since any accumulated heat is readily dissipated upon climbing to altitude. For helicopter application, Froom et al **(7)** have shown that the cooling effects of open cabin doors may reduce WBGTa below WBGTg values when WBGT exceeds 30 ^{o}C during an 1-hour ground stand-by mode. Therefore WBGTg values may be applicable as HIS during this sensitive phase.
With closed cockpit doors and canopies, WBGT ground values for heavy work could also be applied. For large haul aircraft, WBGTg values are again correlated to WBGTa and may serve as HSI.

CONCLUSION

This study has shown that Wet Bulb Globe Temperature Index (WBGT) ground values correlate to WBGT aircraft values in extended range, and WBGT may be used to predict heat stress in ground personnel and aircrew in large haul, of bubble canopy aircraft with cockpit doors or canopy open.
The Fighter Index of Thermal Stress (FITS) at its present form is not applicable on the bubble canopy aircraft with closed doors, and may require further adaptation to Mediterranean type of climatic conditions and to more complex aircrew ensembles.
Thermal stress on aircrew operating bubble canopy aircraft with closed canopies or doors performing exclusive low level – high speed mission may be predictable by WBGT ground values relating to heavy work.

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New Heat and Cold Strain Predictive Indices*

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Summary

New heat and cold strain predictive indices have recently been developed which should be of great military utility. The physiological strain index (PSI), based on rectal temperature (T_{re}) and heart rate (HR), is capable of indicating heat strain online and analyzing existing databases. We assumed that the maximal T_{re} and HR rise during exposure to exercise-heat stress from normothermia to hyperthermia was 3°C (36.5°C to 39.5°C) and 120 beats/min (60 to 180 beats/min), respectively. T_{re} and HR were assigned the same weight functions as follows:

$$PSI=5(T_{ret}-T_{re0})\cdot(39.5-T_{re0})^{-1}+5(HR_t-HR_0)\cdot(180-HR_0)^{-1}$$

where T_{ret} and HR_t are simultaneous measurements taken at any time during the exposure and T_{re0} and HR_0 are the initial measurements. Six independent studies, containing eight different databases were analyzed in order to evaluate PSI for different climatic conditions, hydration levels, types of clothing, exercise intensities, gender and the effects of aging. PSI was capable of significantly differentiating ($P < 0.05$) between all of these conditions and some combinations of these conditions. Our cold strain index (CSI), based on core (T_{core}) and mean skin temperatures ($\overline{T}_{sk}$), is capable of indicating cold strain in real time and analyzing existing databases. T_{core} represents both T_{re} and esophageal temperature (T_{es}). CSI was calculated as follows:

$$CSI=6.67(T_{coret}-T_{core0})\cdot(35-T_{core0})^{-1}+3.33(\overline{T}_{skt}-\overline{T}_{sk0})\cdot(20-\overline{T}_{sk0})^{-1}$$

where T_{core0} and $\overline{T}_{sk0}$ are the initial measurements and T_{coret} and $\overline{T}_{skt}$ are simultaneous measurements taken at any time during the exposure; when $T_{coret} > T_{core0}$, then $T_{coret} - T_{core0} = 0$. Three independent studies containing three different databases were analyzed in order to evaluate CSI for different cold air and cold-water immersion conditions. CSI significantly differentiated ($P < 0.01$) between the conditions for two of these three databases. However, further study is required to possibly adjust CSI for a wider range of cold air and water temperatures, and to consider the effects of physical exercise. Both PSI and CSI rate heat and cold strain on a universal scale of 0-10. Both indices have the potential to be widely accepted and used universally for many military scenarios.

*LTC Daniel S. Moran, Ph.D. developed these new heat and cold strain predictive indices while working at the U.S. Army Research Institute of Environmental Medicine as a National Research Council Fellow.

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Introduction

Over the last century, scientists have attempted to combine environmental parameters and physiological responses to develop a variety of heat stress/strain indices. The existing indices can be divided into two main categories: effective temperature indices that are derived from climatic parameters only (i.e., ambient temperature, wet-bulb temperature, and/or black-globe temperature, etc.), and rational heat indices which incorporate a combination of climatic and physiological parameters (i.e., radiative and convective heat transfer, evaporative capacity of the environment, and/or metabolic heat production, etc.). Although more than 20 heat strain indices have already been developed, none are universally accepted as the physiological strain index with regard to exercise-heat stress. Some of the main reasons for lack of universal acceptance involve a combination of potential problems including the complexity of calculation, the lack of a universal scale, inability to make calculations online, the limited applicability of some indices for diverse climatic conditions, and assumed corrections for protective clothing and different metabolic rates. In 1980, Lee (4) concluded that “Any reader who was hoping for the evolution of a single heat index applicable to all aspects of human endeavor must by now be sadly disappointed”.

Over the last half century, researchers have also attempted to derive a number of different cold stress/strain indices. Less than 10 cold strain indices currently exist, and most of these are based on ambient temperature and wind chill. The most notable is probably that developed by Siple and Passel (18) which is referred to as the wind chill index. This index utilizes the cooling power of the environment by integrating the effects of ambient temperature and wind velocity to assess the convective cooling power. However, wind chill and ambient temperature merely quantify the stress to the unprotected body surface area. Also, the wind chill index is applicable only at wind speeds exceeding 20 m/s, overestimates the cooling power of a nude person, and underestimates the cooling power for a clothed person (8).

The most commonly accepted physiological criterion of heat strain was best defined in 1905 by Haldane (3) as the inability to maintain body core temperature at the level prescribed by the thermoregulatory center. In addition, core temperature has generally been accepted as an appropriate physiological measure for assessing cold strain, and also involved in the categorization of different stages of hypothermia. Therefore, core temperature was assumed to be essential in the development of new physiologically-based indices of heat and cold strain, and the primary thermoregulatory input to these indices. Heart rate (HR) was thought to be an appropriate physiological measure of the cardiovascular strain associated with exercise-heat stress and useful for heat strain index development. Since mean skin temperature (T_{sk}) was found to be rapidly affected by cold exposure, we assumed that this measure could be used to reflect changes in ongoing dynamic heat exchange and useful for cold strain index development.

This report summarizes the development of our new physiological strain index (PSI) which is based on rectal (T_{re}) or in some cases esophageal (T_{es}) temperature and HR (13). PSI has been shown to effectively differentiate the heat strain associated with different climatic conditions, hydration levels, types of clothing including protective clothing, different exercise intensities, gender, and the effects of aging (10, 11, 12, 13, 14, 15). Our new cold strain index (CSI) is based on core temperature (T_{re} or T_{es}) and T_{sk} (8). CSI has been demonstrated to be effective in depicting cold strain for both cold air and cold-water immersion primarily during resting conditions (8). While no significant refinements to PSI appear necessary, CSI may need to be further adjusted to consider a wider range of cold air and water temperatures, and to better consider the effects of physical exercise (2, 8).

PSI and CSI Development/Validation

The new PSI was developed/validated from two different databases collected from subjects who differed in their aerobic fitness and heat tolerance. One of these databases served to develop PSI while the second database from an independent study was used to validate PSI. A detailed description of the development/validation of PSI can be found in a paper published by Moran and colleagues (13); however, a brief description of the approaches taken will be presented.

One hundred healthy young men at different levels of aerobic fitness and heat acclimation volunteered to participate in the study used to develop PSI. The physical characteristics of these men were (mean±SE): age, 20±3 yr; height, 178±10 cm; weight, 74.6±10.5 kg; and, body surface area, 1.92±0.15 m^2. All of these young men were informed as to the nature of the study, potential risks of exposure to exercise in a hot climate, and signed a consent form. These men wore shorts and sport shoes while walking at 1.34 m/s (2% grade) in a hot/dry climate of 40ºC, 40% relative humidity (RH) for 120 min. T_{re} and HR were continuously monitored and recorded at 1 min intervals. Several experiments were terminated when a subject voluntarily withdrew or reached a T_{re} of 39ºC and/or HR exceeded 180 beats/min.

PSI was calculated as follows:

$$PSI=5(T_{ret}-T_{re0})\cdot(39.5-T_{re0})^{-1}+5(HR_t-HR_0)\cdot(180-HR_0)^{-1}$$

where T_{ret} and HR_t are simultaneous measurements taken at any time during the exposure and T_{re0} and HR_0 are the initial measurements. T_{re} and HR which depicts the combined load of the thermoregulatory and cardiovascular systems were assigned the same weight by using a constant of 5. Thus, PSI was scaled to a range of 0-10 within the limits of the following values: $36.5 \leq T_{re} \leq 39.5$ºC and $60 \leq HR \leq 180$ beats/min.

Table 1. Calculated PSI from measured HR and T_{re} obtained from 100 young men exposed to 120 min exercise-heat stress

Strain	PSI	HR, beats/min	T_{re}, ºC	*n*
	0	71±1.0	37.12±0.03	100
No/little	1	90±1.1	37.15±0.04	47
	2	103±1.1	37.35±0.03	81
Low	3	115±1.3	37.61±0.03	80
	4	125±1.4	37.77±0.04	61
Moderate	5	140±1.9	37.99±0.05	28
	6	145±5.3	38.27±0.07	13
High	7	159±1.3	38.60±0.04	5
	8	175	38.7	1
Very high	9			0
	10			0

Values are means±SE (*n* is number of subjects). Heat stress, 40°C, 40% RH, walking 1.34 m/s at 2% grade. No data available for very high strain. From reference 13.

Table 1 depicts the newly-developed PSI applied to the data obtained from the 100 young men performing exercise in the heat. Because these men were not a homogeneous group and varied in their aerobic fitness, heat acclimation status and tolerance to exercise-heat stress, data analysis was applied individually.

The new CSI constructed to evaluate the impact of cold stress used the same basic concepts involved with PSI. Because $\bar{T}_{sk}$ changes very quickly in response to cold environments and T_{core} (T_{re} or T_{es}) reflects the thermoregulatory strain, we decided that these two parameters should adequately depict the cold strain resulting from either cold air or cold-water immersion. The weighting constants for these two physiological parameters were similar to that described for mean body temperature or 6.67 for T_{core} and 3.33 for $\bar{T}_{sk}$. CSI was scaled to a range of 0-10 within the limits of the following values: $35 \leq T_{core} \leq 38°C$ and $20 \leq \bar{T}_{sk} \leq 35°C$. Therefore, CSI was calculated as follows:

$$CSI=6.67(T_{coret}-T_{core0})\cdot(35-T_{core0})^{-1}+3.33(\bar{T}_{skt}-\bar{T}_{sk0})\cdot(20-\bar{T}_{sk0})^{-1}$$

where T_{core0} and $\bar{T}_{sk0}$ are the initial measurements and T_{coret} and $\bar{T}_{skt}$ are simultaneous measurements taken at any time during the exposure; when $T_{coret} > T_{core0}$, then $T_{coret} - T_{core0} = 0$. Three different databases were analyzed in order to evaluate CSI for different cold air and cold-water immersion conditions during rest.

Table 2. Evaluation and categorization of different heat and cold strains by PSI and CSI, respectively

Strain	PSI/CSI
No/little	**0**
	1
	2
Low	**3**
	4
Moderate	**5**
	6
High	**7**
	8
Very high	**9**
	10

From reference 12.

Table 2 illustrates the heat and cold strain verbal categorizations associated with the numerical values for PSI and CSI. This universal scale from 0-10 was originally derived for PSI but has also been found to be applicable to CSI.

Results and Discussion

Physiological Strain Index. Six independent studies, containing eight different databases were analyzed in order to evaluate PSI for different climatic conditions, types of clothing including protective clothing, exercise intensities, hydration levels, gender and aging. In the first study, Montain and colleagues (7) studied seven young men wearing full (clo=1.5) or partial (clo=1.3) protective clothing who performed light exercise for 180 min in either hot/dry or hot/wet climatic

conditions (43°C, 20% RH; 35°C, 50%RH, respectively). As shown in Figure 1, PSI significantly differentiated ($P < 0.05$) between the heat strain in the hot/dry and hot/wet climates, and also between the full (MOPP IV) and the partial (MOPP I) protective clothing configurations.

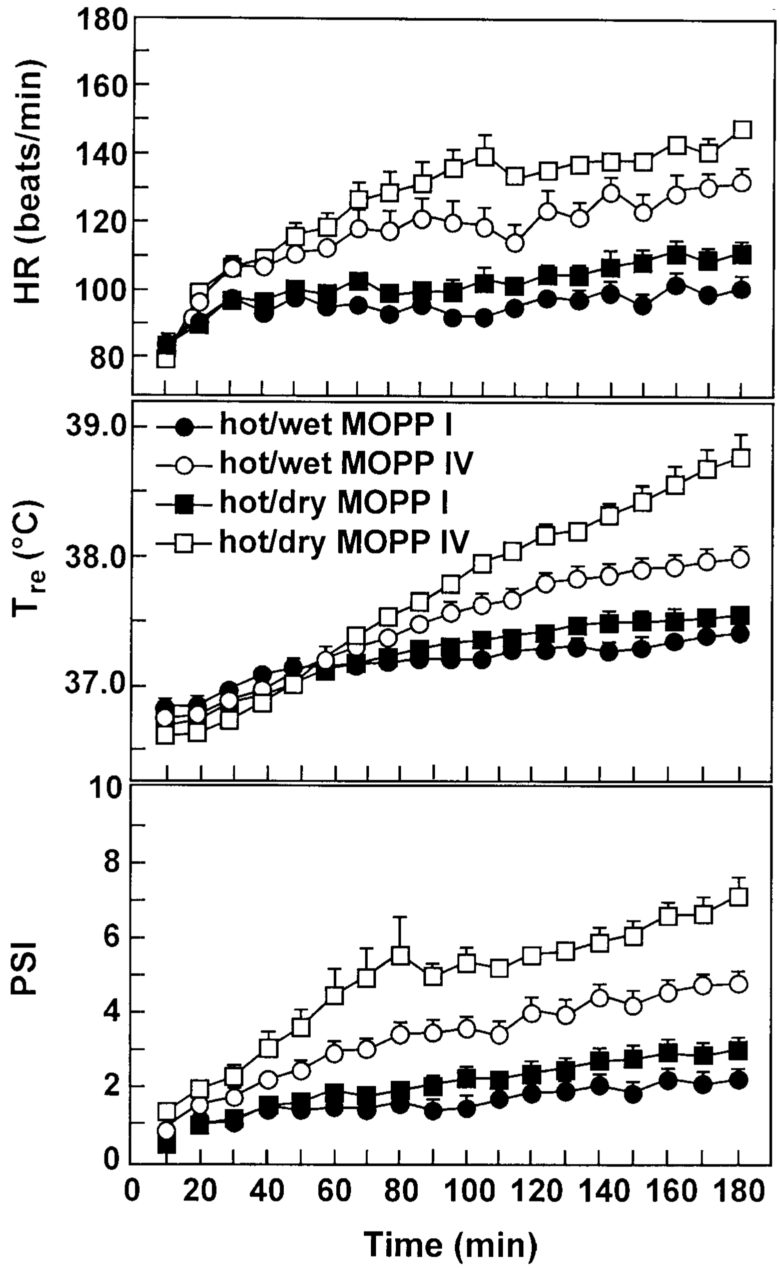

Figure 1. Comparison between HR (top), T_{re} (middle) and PSI (bottom) in hot-dry and hot-wet climates wearing partial (MOPP I) and full (MOPP IV) protective clothing. From reference 15.

Evaluation of PSI for different levels of dehydration during prolonged exercise was completed using a database from Montain and Coyle (5) within the range of HR=55-175 beats/min, T_{re}=36.8-39.7°C and T_{es}=36.4-39.2°C. Eight endurance-trained male cyclists (age, 23±3 yr; weight, 72.2±11.6 kg; $\dot{V}O_2max$, 66.2±7.6 $ml \bullet kg^{-1} \bullet min^{-1}$) cycled at a power output eliciting 62-67% $\dot{V}O_2max$ for 120 min in a warm climate (33°C, 50% RH). Each man completed four

experimental exposures while ingesting different volumes of fluid during exercise: no fluid, or a volume that replaced 20%, 50% or 80% of the fluid lost in sweating resulting in 4.2%±0.1, 3.4%±0.1, 2.3%±0.1, or 1.1%±0.1 body weight loss (BWL), respectively after 120 min cycling. Figure 2 shows that T_{re} was generally elevated in proportion to the magnitude of the hypohydration levels and the four trials were significantly different from each other ($P < 0.05$) with the exception of the 3.4% and 4.2% BWL exposures. HR increased progressively during exercise at the different hypohydration levels; however, HR at 120 min of exercise was not significantly different between the exposures of 1.1% and 2.3% BWL, and the 3.4% and 4.2% BWL. Figure 2 illustrates PSI correctly discriminated between the four different hypohydration levels at this exercise intensity.

Montain and colleagues (6) studied nine young acclimated men (age, 24±2 yr; height, 176±3 cm; weight, 81.7±4.5 kg; $\dot{V}O_2max$, 57±2 $ml \bullet kg^{-1} \bullet min^{-1}$) who completed nine 50 min exercise exposures in a warm climate (30°C, 50% RH). These exposures consisted of treadmill exercise at three intensities: 25, 45 and 65% $\dot{V}O_2max$ when either euhydrated or hypohydrated by 3 and 5% of each subjects' baseline body weight. Table 3 shows that PSI correctly categorized the heat strain in rank order to the various combinations of exercise intensity and hydration level. The euhydration exposures were generally ranked as little or low strain with values of 1.6±0.2 to 3.1±0.3. The 3% BWL exposures were ranked as moderate strain and ranged from 4.3±0.2 to 6.4±0.4 while the 5% BWL exposures were categorized with high or very high strain ranging from 7.4±0.3 to 10.0±0.9.

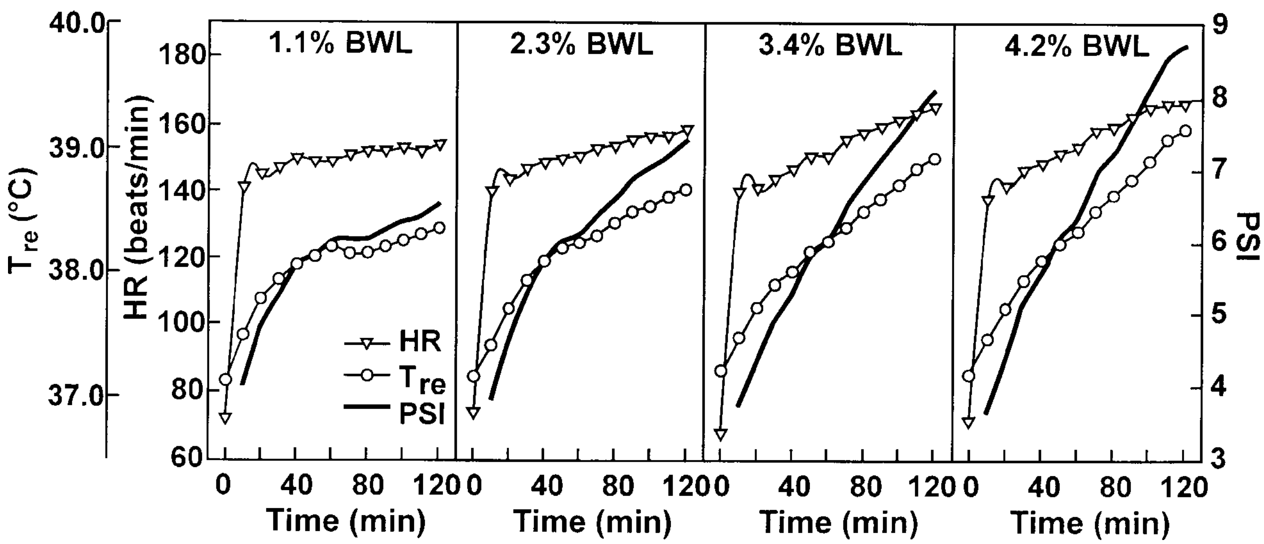

Figure 2. The PSI calculated from T_{re} and HR applied to mean values obtained from men exposed to exercise-heat stress at 4 different levels of hypohydration. From reference 11.

Table 3. Calculated PSI depicting the effects of work intensity and/or hydration level

Work Intensity, % $\dot{V}O_2max$	Hydration, %BWL	PSI Units	PSI Strain
25	0	1.6±0.2	Little
	3	2.2±0.3	Little
	5	3.1±0.3	Low
45	0	4.3±0.2	Low
	3	5.5±0.4	Moderate
	5	6.4±0.4	Moderate
65	0	7.4±0.3	High
	3	9.1±0.9	Very high
	5	10.0±0.9	Very high

Unit values are means±SE. Nine men performed 50 min exercise in the heat (30°C, 50% RH) at different exercise intensities (25, 45 and 65% $\dot{V}O_2max$) and different hydration levels (euhydration and hypohydration at 3 and 5% body weight). From reference 11.

Moran and colleagues (12) also evaluated PSI for gender differences under various combinations of exercise intensity and climate. Two groups of eight men each were formed according to $\dot{V}O_2max$ where the first group of men (M) was matched to a group of nine women (W) with similar ($P > 0.001$) $\dot{V}O_2max$ (46.1±2.0 and 43.6±2.9 $ml \bullet kg^{-1} \bullet min^{-1}$, respectively). The second group of men (FM) was significantly ($P < 0.001$) more aerobically fit than M or W with $\dot{V}O_2max$ of 59.1±1.8 $ml \bullet kg^{-1} \bullet min^{-1}$. No significant differences ($P < 0.05$) existed between these three groups for age, weight, height and body mass index. Therefore, the relative exercise intensity (% $\dot{V}O_2max$) during these experiments was the same for M and W but significantly lower for FM. Subjects completed a matrix of nine experimental combinations consisting of three different exercise intensities for 60 min [low, moderate and high (300, 500 and 650 W, respectively)] each at three different climates [comfortable, hot wet and hot dry (20°C, 50%RH; 35°C, 70%RH; and 40°C, 35%RH)].

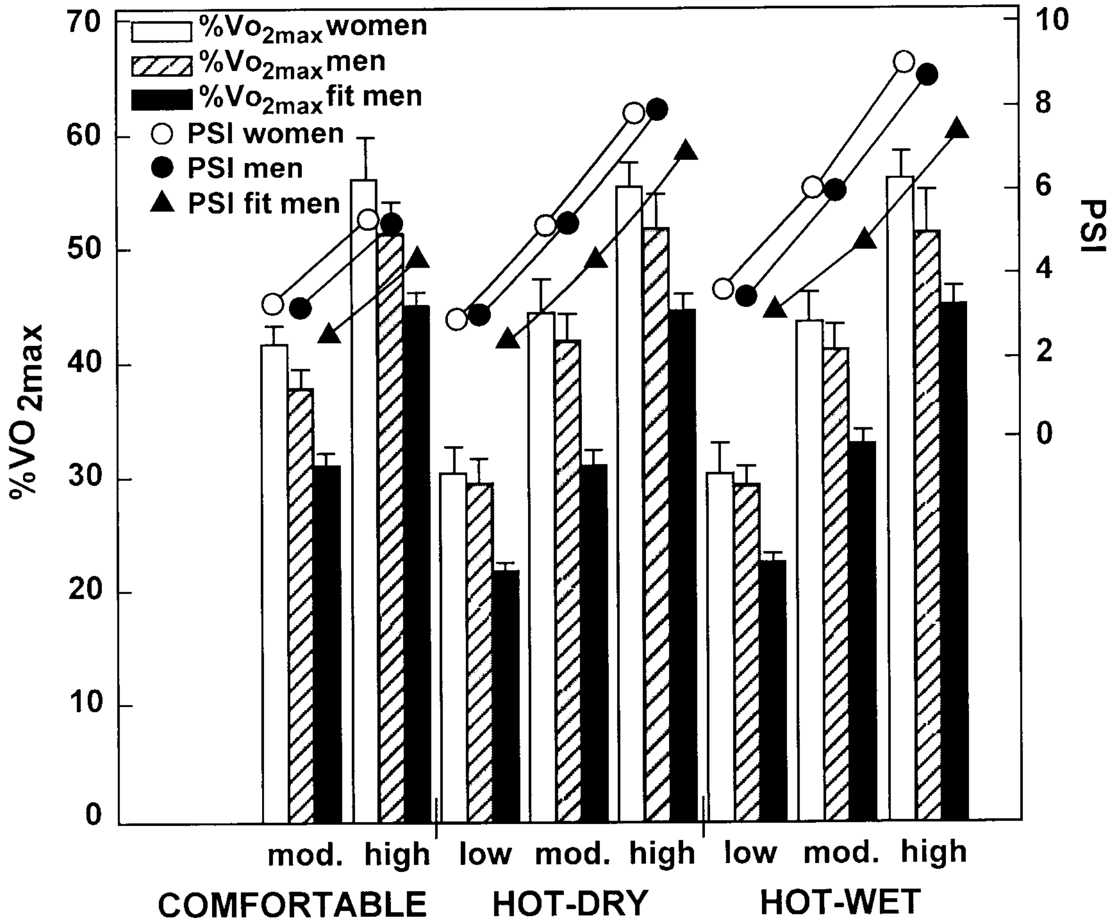

Figure 3. PSI and relative $\dot{V}O_2max$ (mean±SE) after 60 min for the three groups of men (men=M and fit men=FM) and women (women=W) during the various combinations of exercise intensity and climate. From reference 12.

The relative $\dot{V}O_2max$ and simultaneously calculated PSI are depicted in Figure 3. Generally, significant differences ($P < 0.01$) were found in $\%\dot{V}O_2max$ between the different exercise intensities. However, no significant differences ($P > 0.05$) were found between the same exercise intensities for the different climatic conditions. In all experimental exposures, the lowest $\%\dot{V}O_2max$ values were calculated for FM and found to be significantly different ($P < 0.05$) from W or M. No significant differences were found in $\%\dot{V}O_2max$ between W and M. High correlations were found between $\%\dot{V}O_2max$ and PSI in two different statistical analyses. First, for the different exercise intensities under the same climatic conditions (r=0.99), and second, when compared between the different groups for the same exercise intensity and climatic condition (r=0.96).

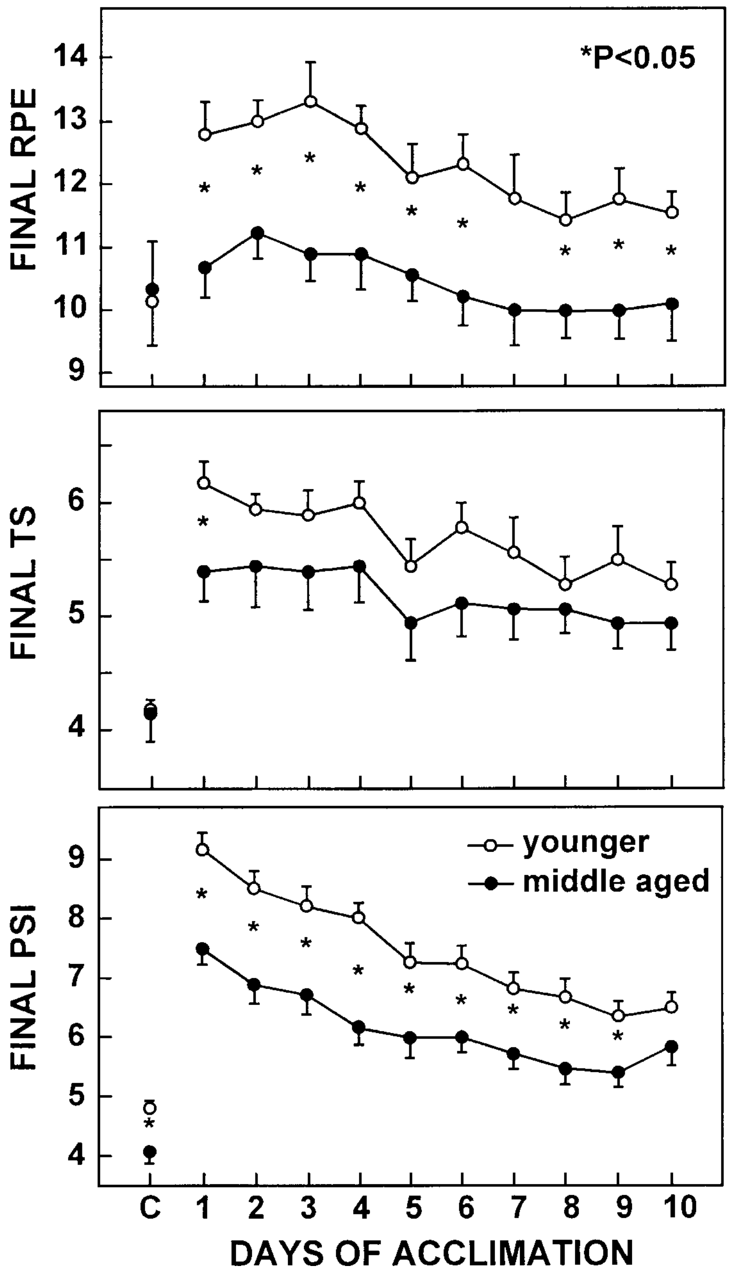

Figure 4. Mean (±SE) final rated perceived exertion (RPE), thermal sensation (TS) and PSI of 9 young and 9 middle-aged men during the control (C) day and each of 10 exercise-heat acclimation days. From reference 10.

Evaluation of PSI for young (21±1 yr) and middle-aged (46±2 yr) men during 10 days of exercise-heat acclimation was conducted using a database from Pandolf and colleagues (17). Two groups of 9 men each were matched (P > 0.05) for $\dot{V}O_2max$ (52.9±1.7 and 51.3±3.1 $ml \bullet kg^{-1} \bullet min^{-1}$, young and middle-aged, respectively) and physical characteristics (weight, 76.3±2.2 and 82.2±3.2 kg; surface area, 1.90±0.03 and 2.01±0.04 m^2 for the same two groups, respectively). Subjects were heat acclimated for 120 min by treadmill walking (1.56 m/s, 5% grade) for 10 consecutive days in a hot-dry (49°C, 20% RH) climate. The exercise intensity required ~45% $\dot{V}O_2max$ for both groups.

Heat acclimation was preceded by an identical protocol in a comfortable climate (22°C, 50% RH). Although not shown, final T_{re} and HR decreased ($P < 0.05$) for both groups from the first to last acclimation day (17). Final T_{re} was higher ($P < 0.05$) for the young men during each of the first 4 acclimation days and displayed a trend ($P > 0.05$) to be higher on the remaining acclimation days while final HR was higher ($P < 0.05$) for the young men on days 1, 2, 4, 5 and 7 of acclimation and also showed a trend ($P > 0.05$) to be higher on the other acclimation days (17). Rated perceived exertion (RPE, 1) and thermal sensation (TS, 19) were also measured during these experiments. Figure 4 shows that final values for RPE, TS and PSI all had higher strain for the younger compared to the middle-aged men throughout the 10-day acclimation. Significant differences ($P < 0.05$) for RPE were found on all acclimation days except day 7, whereas, for TS significant differences were noted only on day 1. PSI was higher ($P < 0.05$) for the younger men on days 1-9. Thus, PSI not only reflected the T_{re} and HR responses between these two groups during acclimation but also showed a strong relationship with the perceptual responses from these experiments (12).

Cold Strain Index. Three independent studies involving three different databases were analyzed in order to develop and evaluate CSI for different cold air and cold-water immersion conditions (8). CSI seemed to adequately describe the resultant cold strain during rest but might need to be adjusted to consider the effects of physical exercise.

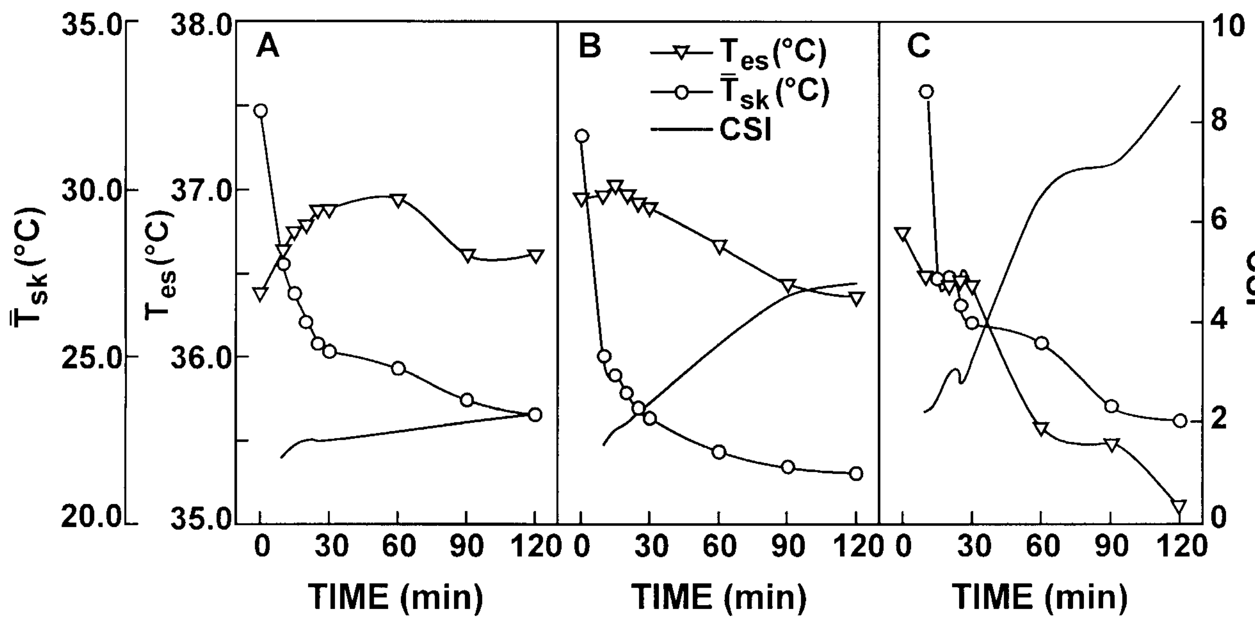

Figure 5. Cold strain index (CSI) calculated from esophageal temperature (T_{es}) and mean skin temperature ($\bar{T}_{sk}$) applied to three young men exposed to the same cold-air stress (7°C, 40% RH; data from reference 16). A, B and C refer to subjects 1, 2 and 3, respectively. From reference 8.

Nine young men participated in a study published by O'Brien and colleagues (16) which was used to develop the new CSI. The physical characteristics of these men were (mean±SE): age, 24±2 yr; height, 178±2 cm; weight, 77±4 kg; and $\dot{V}O_2max$, 55±1 $ml \bullet kg^{-1} \bullet min^{-1}$. These men were dressed in shorts, socks and shoes during the experimental trials which consisted of 30 min of rest in comfortable climatic conditions (25°C) followed by 120 min of rest in cold air (7°C, 40% RH). Because these men were not a homogeneous group and cold exposure resulted in large individual differences in physiological responses, data were analyzed individually (8).

Figure 5 depicts the data obtained from O'Brien and colleagues (16) on three different subjects exposed to the same cold-air conditions at the same hydration state but at different cold-strain levels during these cold exposures. Little cold strain, rated by CSI as 2, was observed for subject A; low-to-moderate strain which gradually increased and after 120 min reached 4.8 was seen for subject B; and, high cold strain which almost linearly increased with exposure time and ended as 8.7 was seen for subject C (8).

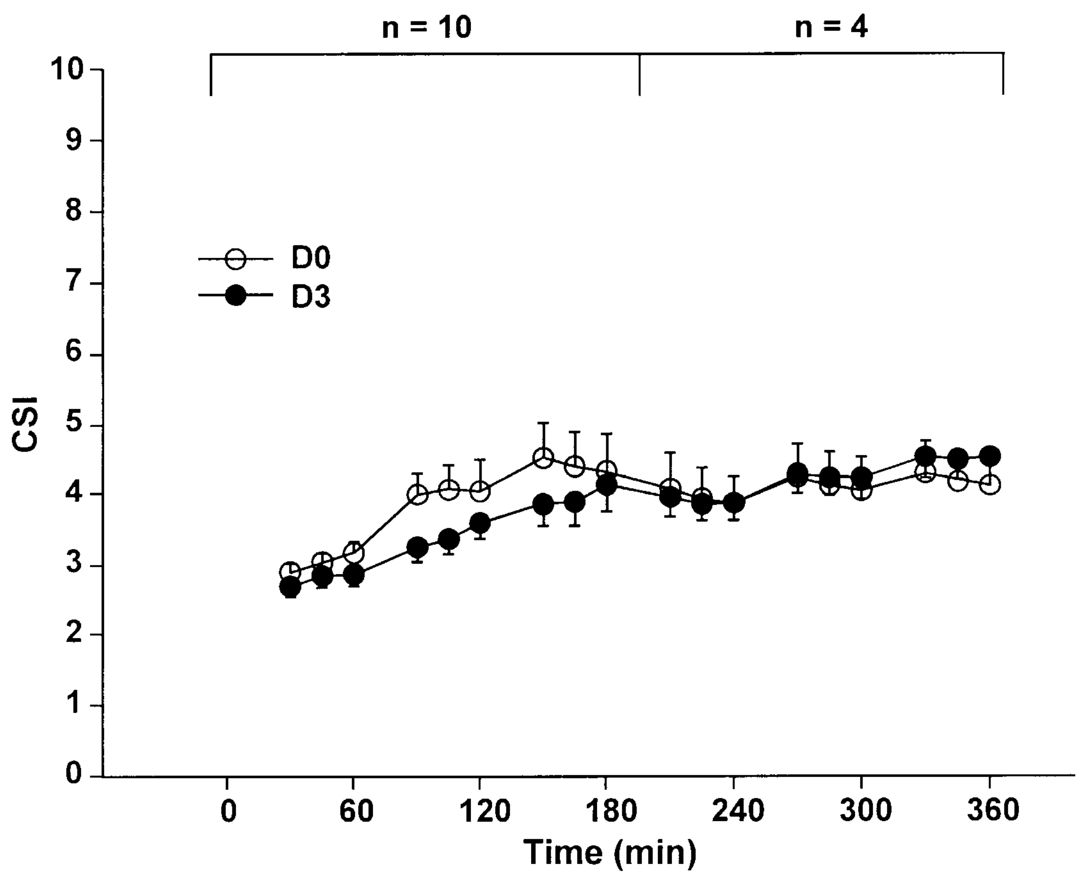

Figure 6. Cold strain index (CSI) versus time during exercise-cold exposure before and after 3 days of exhaustive exercise. Data from 0 to 180 min from n=10 men, data from 190 to 360 min from n=4 men. From reference 2.

In a recent study, Castellani and colleagues (2) evaluated 10 young men (mean ±SE: age, 24±1 yr; height, 177±2 cm; weight, 82.8±3.6 kg; %fat, 16.4±1.9%; $\dot{V}O_2$ peak, 56.0±1.8 $ml \bullet kg^{-1} \bullet min^{-1}$; and, body surface area, 1.99±0.05 m^2) who exercised in cold-wet conditions for 6 hr before (D0) and after 3 days of exhaustive exercise (D3). Each hour of the cold-wet conditions consisted of 10 min standing in rain (5.4 cm/hr, 5°C air) followed by 45 min treadmill walking (1.34 m/s, 5.4 m/s wind, 5°C air). Although not shown, the change in T_{re} across time was greater ($P < 0.05$) for D3 versus D0, and the change in $\overline{T}_{sk}$ was less ($P < 0.05$) for D3 versus D0. Figure 6 shows the corresponding CSI responses for these same experiments. Although CSI increased across time, the index at the end of both trials (D3=4.6±0.6, D0=4.2±0.8) was similar ($P > 0.05$). Thus, although $\overline{T}_{sk}$ was 1.3°C higher ($P < 0.05$) and T_{re} was 0.3°C lower ($P < 0.05$) on D3 versus D0, CSI could not discriminate the greater heat loss that occurred on D3. These findings would seem to indicate that when

vasoconstrictor responses to cold are altered such as following exhaustive exercise, CSI may not adequately quantify the associated cold strain.

Conclusions

PSI has been shown to adequately reflect the associated heat strain for different climatic conditions, types of clothing including protective clothing, various hydration levels, different exercise intensities, gender, and the effects of aging. In addition, adjusted PSI can discriminate the heat strain in non-human species such as rats during exercise-heat stress (9). Thus, PSI does not seem to require any significant refinements. CSI has been shown to be effective in depicting cold strain for both cold air and cold-water immersion during resting conditions. However, CSI may need to be further adjusted to better consider the effects of physical exercise, and also a wider range of cold air and water temperatures. We speculate that the addition of HR to CSI as a third component to this index could potentially be the proper adjustment. Nevertheless, both indices have the potential to be widely accepted and used universally for many military scenarios.

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Disclaimer

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Integration Between the Environmental Stress Index (ESI) and the Physiological Strain Index (PSI) as a Guideline for Training

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Summary

A new environmental stress index (ESI), based on ambient temperature (T_a), relative humidity (RH) and global radiation (GR), was recently suggested as a potential substitute for the wet bulb globe temperature (WBGT) index. This new stress index, found to have a high correlation to WBGT, is constructed from fast reading meteorological response sensors (T_a, RH, and GR) that take only a few seconds to reach equilibrium. Furthermore, the ESI is the first stress index using direct measurements of solar radiation and is calculated as follows:

$$ESI=0.63T_a-0.03RH+0.002SR+0.0054(T_a\cdot RH)-0.073(0.1+SR)^{-1}$$

The recently suggested physiological strain index (PSI) is capable of indicating heat strain online and analyzing existing databases. The PSI is constructed from rectal temperature (T_{re}) and heart rate (HR) as follows:

$$PSI=5(T_{ret}-T_{re0})\cdot(39.5-T_{re0})^{-1}+5(HR_t-HR_0)\cdot(180-HR_0)^{-1}$$

where T_{re0} and HR_0 are the initial T_{re} and HR, and T_{ret} and HR_t are simultaneous measurements taken at any time. The PSI is scaled from 0-10, whereby each variable PSI_{HR} or PSI_{Tre} which represent the cardiovascular and the thermoregulation systems respectively, can contribute up to 5 units to the overall strain assessment.

The purpose of this study was to develop guidelines based on ESI and PSI for work-rest cycles (WRC) during training. In order to integrate PSI and ESI, we decided to use only the PSI_{HR} component, which represents the metabolic rate and the strain reflected by the cardiovascular system. Furthermore, PSI_{HR} is easier to measure, is easier to implement and simplifies the integration with ESI. Concomitantly, it categorizes the strain between 0-5, the higher the value, the higher the strain.

Introduction

Training schedules that include work-rest cycles are a function of two main variables. The first is the exercise intensity and the second is climatic conditions. A combination of these two variables at any "time point" determines the strain and the stress for an individual. Recently, Moran and colleagues (11) introduced a new physiological strain index (PSI) based upon the summation in equal weights of individual strains in core temperature (T_c) and heart rate (HR), representing the combined strains of thermoregulatory and cardiovascular systems. Each strain system was scaled between 0-5. The PSI is thus scaled 0-10, and can be used on-line or during data analysis. The PSI can be applied at any time, including rest or recovery periods, whenever T_c and HR are measured (11). In a recent series of studies, PSI successfully evaluated the strains in different clothing ensembles and climatic conditions during heat stress, during different levels of hydration and exercise intensity, for gender during heat stress, and for different age groups during 10-days of acclimatization and acute exercise heat-stress (6, 10, 11). Furthermore, this index, when adjusted for animal values, successfully rated and correctly discriminated between trained and acclimated rats exposed to exercise-heat stress. (5)

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The combination of different climates, impermeable garments, and hydration levels during different exercise intensities is a challenge for assessment of the individual physiological strain. However, in two recent studies (6, 11), when different heat strain indices were applied to various independent databases, the other indices were limited in their ability to quantify the heat strain, whereas PSI was successful at all levels of heat exposure. PSI differs from previous indices. It is easier to interpret and use than other indicess available, and includes the ability to assess rest and recovery periods. PSI overcomes the shortcomings of previously described indices and can be used over a wide range of conditions.

Heat stress evaluation is generally determined through meteorological parameters that enable the estimation of the influence of several environmental factors on thermal comfort and physiological ability. The variables included in heat stress indices and their relative weights have changed over the years. In 1957, Yaglou and Minard (14) introduced the Wet Bulb Globe Temperature (WBGT) index, which gained popularity mainly due to its simplicity and convenience of use. This index is obtained mainly from three parameters: black globe temperature (T_g) which reflects the solar radiation, wet bulb temperature (T_w), and dry bulb temperature (T_a). This index is calculated as follows:

$$WBGT=0.7T_w + 0.2T_g + 0.1T_a$$

As noted before, the index has gained immense popularity over the years. The WBGT is in use in the field by the US Army and is the index from which training safety orders are based (3). It has been adapted by the World Health Organization (WHO) and the American College of Sports Medicine (ACSM) (1). In 1972, the National Institute for Occupational Safety and Health (NIOSH) set it as the criterion for occupational exposure to a hot environment (12). In 1982, it was approved by the ISO organization as an international standard for heat load assessment. Later on, work-rest regime regulations were made based on this index. However, WBGT was found to be limited in evaluating heat stress due to the inconvenience of measuring T_g (7). It is important to note the correlation of this index to physiological responses was only partially tested and was based mainly on the correlation between the number of heatstroke cases during army training and the heat load as calculated by the WBGT (14).

In 2001, Moran et al. (9) inroduced a new environmental stress index (ESI) based on measuerements of T_a, relative humidity (RH), and solar radiaton (SR) as follows:

$$ESI=0.63T_a-0.03RH+0.002SR+0.0054\,(T_a\cdot RH)-0.073(0.1+SR)^{-1}$$

This newly developed index was validated by using large databases and was found to be highly correlated to the WBGT index (9).

ESI differs from other indices that have been suggested in the past for two main reasons. First, ESI is based on SR and RH, aside from using T_a. In fact, there are indices based on indirect measurements of SR and RH. For example, the WBGT uses T_g for evaluating SR, and T_w is used for estimation of RH. However, the ESI as a stress index, for the first time uses direct measurements of SR and RH. Second, the three meteorological variables used in ESI are characterized by fast reading responses and take only a few seconds to reach equilibrium. Recently, the ESI was validated with measurements from an infra-red (IR) light sensor for global radiation. It was concluded in that study that an IR light sensor can be used as a potential substitute for T_g which is incorporated in the WBGT (8).

The purpose of this study was to develop easy-to-use guidelines for work-rest cycles during training based on the integration of PSI and ESI. Using these guidelines for different combinations of different levels of exercise intensity and environmental load should help in preventing heat casualties.

Methods

The primary index for physiological assessment used in this study is the PSI (11). However, in this study we only used the PSI_{HR} component as follows:

$$PSI_{HR} = 5(HR_t-HR_0)\cdot(180-HR_0)^{-1}$$

As a consequence, PSI_{HR} assessment ranged from 0-5, the higher the value, the higher the strain.

The newly developed ESI defined in this study uses the same heat categories and color-coded assessment as the WBGT index. Even though ESI is constructed from different variables than the WBGT, the outcome values are the same for both indices, including the heat category assessment of 1-5.

The length of work-rest cycles (WRC) at different WBGT conditions during training was estimated from the Montain et al. (4) study. The WRC were set from predicted core temperature and other physiological responses to work in the heat (13), and were set for preventing T_c from rising above 38.5°C during 4 hours of sustained training. These values are the outcome of the predictive models for healthy, euhydrated and reasonbly fit soldiers.

Maximal HR (HR_{max}) was calculated as suggested by the American College of Sports Medicine Guidelines as follows (2): HR_{max} = 220-age. Accordingly for each PSI_{HR} assessment, the matched HR range was calculated.

Results

Since PSI is constructed from T_{re} and HR, each of these individual parameters can contribute different weight to the index, but up to a maximum of 5 units. However, when T_{re} measurement is not possible or convenient to use, we suggest as an optional alternative using only PSI_{HR} for strain assessment. The PSI_{HR} ranges from 0-5, stands for the cardiovascular load and represents the metabolic state and strain by HR in minimal response time. For applicable usage of PSI_{HR} for different individuals at different physical fitness, we add for each strain level the matched range of HR values (Table 1). These HR values are derived from calculated HR_{max} for persons of 20 and 40 yrs (HR_{max} of 180 and 200 beats/min, respectively) at low and moderate physical fitness.

Table 1: Strain categorization by the heart rate component of the physiological strain index (PSI_{HR}) and the expected HR range for each strain category.

Strain	PSI_{HR}	HR (beats/min)
No/Little	**0-1**	**<95**
Low	**2 (Green)**	**96-120**
Moderate	**3 (Yellow)**	**121-145**
High	**4 (Red)**	**146-170**
Very high	**5 (Black)**	**>171**

Using the same WBGT assessment and based on Montain et al. (4) guidelines for work-rest cycles (WRC), we constructed a matrix, which, according to the heat stress (ESI), recommends WRC the for different exercise intensities depicted by PSI_{HR} (Figure 1). The strain assessment by PSI_{HR} uses the same color-coded categorization as the WBGT index.

ESI	T_a (°F) / WRC (min)	PSI_{HR} 50/10	40/20	30/30	20/40
1	78-81.9	<4.5	<4.5	<4.5	<4.5
2 (Green)	82-84.9	<4	<4.5	<4.5	<4.5
3 (Yellow)	85-87.9	<3	<4	<4.5	<4.5
4 (Red)	88-89.9	<2	<3	<4	<4.5
5 (Black)	>90	<1	<2	<3	<4

Figure 1: Recommended time (min) for work-rest cycles at different heat categories assessed by the environmental stress index (ESI) and by the heart rate component of the physiological strain index (PSI_{HR}).

According to the heat category calculated by ESI and the requested strain assessed by PSI_{HR}, we can locate the correct cell in the matrix depicted in Fig.1, which recommends the work-rest cycles. The numbers (1-4.5) in the color-coded matrix represent the allowed strain according to the ESI and the WRC (e.g., for ESI=3 and WRC=50/10, exercise intensity of PSI_{HR}<3 is allowed, where according to Table 1, HR=121-145 beats/min).

These findings suggest simple guidelines for different strains at different levels of environmental stress. However, further evaluation is required to possibly adjust this matrix for different age groups, clothing and women.

Discussion

In this study, we integrate between two new indices for strain and stress assessment into an easy-to-use visualized table. The integration between these two indices can serve as a guideline that should be easy to interpret and to implement for soldiers during training in order to prevent heat casualties.

The shortcoming of this work is the strain evaluation by PSI_{HR}. In our previous works, we emphasize the importance of strain evaluation by the cardiovascular and the thermoregulation systems presented by T_c and HR, whereas in this study we only use PSI_{HR} for strain assessment. We still believe that for more accurate strain assessment we should use PSI. However, under various circumstances and in some scenarios, T_c measurement is not practical or convenient. Therefore, only HR measurement that immediately represents the metabolic rate and the strain reflected by the cardiovascular system can be used for strain assessment. In addition, HR is easier to measure, is easier to implement and it can be measured by the individual himself. Since the purpose of this work is to develop guidelines for work-rest cycles in order to help in preventing heat casualties from excessive heat, we should expect a practical and easy-to-use guideline. We believe that the PSI_{HR} component can serve as a suitable alternative for PSI in circumstances where T_c measurement cannot be taken.

The suggested matrix based on PSI_{HR} and ESI is an attempt to give the decision maker an easy tool to use as a guideline. However, since this is the first study regarding the integration of PSI and ESI,

further studies should be made which consider different levels of physical fitness, types of clothing, hydration status, and acclimatization. In addition, it is expected to implement the suggested matrix for fluid replacement quantities.

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Physio-Med Web: Real Time Monitoring of Physiological Strain Index (PSI) of Soldiers During an Urban Training Operation

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Summary

This field study of simulated urban combat explored the array of issues associated with the collection and use of real-time physiologic data. Six male soldiers (age = 22±4y [mean±SD]; ht = 172±5 cm; wt = 69.3±11.6 kg; %body fat = 13.9±6.9; load carried = 19.0±2.9 kg) were monitored in real-time during a simulated attack on the McKenna Military Operations in Urban Terrain (MOUT) facility at the Dismounted Battlespace Battle Lab, Ft. Benning, Georgia. Physiological strain index (PSI), derived from heart rate (HR) and core temperature (Tcore), was used to monitor thermal/work strain (Moran et al., Am. J. Physiol. 275:R129-R134, 1998). Meteorologic conditions: air temp = 21 to 24 ^{o}C; relative humidity = 55-65%; solar radiation = 150-430 W/m ^{2} (estimated WBGT = 19 to 23 ^{o}C). Methods: Tcore was measured by ingested radio telemetry pill, and HR was measured electrocardiographically. Data from these ambulatory sensors was transmitted through a wireless personal area network (PAN) to a control facility where the PSI of each soldier was displayed during the two hour simulated attack. Results: initial PSI = 2 (range: 0 to 3.5), peak = 5 (3.5 to 6.5), recovery = 3.5 (2 to 5). Heart rate (HR): initial = 80 bpm (60 to 110), peak = 165 (140 to 185), recovery = 105 (95 to 125). Core temperature: initial 37.5 ^{o}C (36.8 to 37.9 ^{o}C), peak = 37.9 ^{o}C (37.3 to 38.5 ^{o}C), with limited decreases with 30 min of recovery. Conclusions: PSI appears to be a sensitive indicator of cardiovascular and thermal strain; real-time PSI has potential value in military operations where heat strain is a significant risk. However, significant sensor, PAN, and data management and modeling work remains to be done before the routine use and dissemination of physiologic information is practical for the dismounted warfighter.

Introduction

This study explored the array of issues associated with the collection and use of real-time physiological strain index (PSI) data from soldiers engaged in simulated urban combat. This work was part of a larger “Smart Sensor Web” study exploring broad issues of sensor data management in an urban battlefield.

In most scientific studies, ambulatory sensor data is stored for post hoc analysis. However, near real-time physiologic data collection and analysis is needed for certain militarily and civilian applications. In particular, combat casualty care needs real-time monitoring for remote detection of ballistic wound events, remote life sign detection, and remote triage. Thermal/work strain monitoring may also be useful for warfighters, space flight personnel, firefighters, or civilians working under thermally stressful conditions.

The US Army’s need for physiological monitoring, the current approach to thermal/work strain management, and the Department of Defense heat stoke/sun stroke injury rates are noted below. In addition, the PSI and the issues associated with real-time collection and use of ambulatory physiologic data are discussed. These include: (a) designing comfortable wearable sensors that reliably collect, process, and output Tcore and HR data, (b) implementing wireless Personal Area Network (PAN) transmission of sensor data to a central hub for storage and long range re-transmission to a central control facility, and (c) developing new data base and data mining techniques to manage the large amounts of time series information generated by wearable monitors.

Overview of physiological data requirements and current doctrine

From a broad perspective, military field commanders, medics and, perhaps most importantly, individual warfighters need operationally-relevant performance and health status indicators to avoid casualties. When combat casualties occur, remote life sign detection and remote triage capabilities are needed. In particular, new approaches are needed to improve sleep management,

ensure adequate water intake, improve thermal/work stress management, and avoid heat and cold injuries.

Thermal/work strain is typically managed through work/rest cycle and water intake guidance. For example, in the US Army Field Manual 21-10, a table of Fluid Replacement Guidelines for Warm Weather Training shows work/rest cycles and water intakes for various heat categories and WBGT indexes (Table 3-1 on page 3-4 of Field Manual FM 21-10; http://www.adtdl.army.mil/cgi-bin/atdl.dll/fm/21-10/fm21-10.htm). However, in reality, these guidelines are often not followed when there is a hot weather mission to perform. Water availability may be limited, and water consumption may not be adequately monitored. The consequence is a steady stream of serious and costly heat injuries.

Heat stroke/sun stroke injury rates can be estimated from the Defense Medical Epidemiological Database DMED data base (http://amsa.army.mil) for a population of about 1.39 M warfighters from all services. Over the past 10 years, there have been about 878 heat stroke/sun stroke injuries, with the majority from the Army (511) and US Marine Corps (300). Over the past three years (1998-2000), 384 heat stroke/sun stroke injuries have occurred. Current estimated cost per affected soldier is US$132,000, based on duty days lost, and the cost of hospitalization, replacement, and disability. In terms of dollars alone, this is roughly a US$10M/y problem. Clearly, exploring the use of PSI, and developing new ways to manage thermal strain and reduce heat casualty rates, is warranted.

Physiological Strain Index (PSI) algorithm

The physiologic strain index (PSI), derived from core temperature (Tcore) and heart rate (HR), is simple to calculate, and is uniquely suited to real-time "on-the-fly" monitoring of thermal/exercise heat strain. The PSI reflects combined cardiovascular and thermoregulatory strain on a universal scale of 0 to 10 (13), and appears sensitive to the various influences of climatic conditions, clothing, exercise intensity, hydration state, age, and gender (see Pandolf and Moran, in these proceedings). The PSI algorithm assumes maximum acceptable increases in Tcore and HR of, 3 °C (36.5 °C to 39.5 °C) and 120 beats/min (60 to 180 beats/min), respectively. These upper limits reflect Tcore and HR bounds defined by the USARIEM Institutional Review Board for directed experiments with humans. The two constants "5", preceding the two main terms of the index, reflect the equal influence of Tcore and HR on PSI. That is,

$$PSI = 5(Tcore_t - Tcore_0) \times (39.5\text{-}Tcore_0)^{-1} + 5(HR_t - HR_0) \times (180\text{-}HR_0)^{-1},$$

where Tcoret and HRt are simultaneous measurement taken at any time during the exposure, and Tcore0 and HR_0 are baseline measurements (13).

Core temperature and heart rate sensors

Pulmonary artery, esophageal, and rectal temperatures are valid and widely accepted ways of measuring Tcore (8, 16, 18), but are not suited for use in ambulatory individuals. Tcore estimates by tympanic and axillary temperatures are imprecise (7) and likely to be affected by the variable microclimates experienced by soldiers. Fortunately, telemetry pills provide a valid and field-expedient method of measuring Tcore. Ingested telemetry pill temperatures, under conditions of rising and falling body temperature, closely correlate with esophageal and rectal temperatures (15).

The thermometer pill used in the present study is a very low power radio frequency transmitter where broadcast frequency (~260 kHz) varies with temperature (U.S. patent No. US4844076, issued Aug. 26, 1988; CorTemp™, Human Technologies Inc., Palmetto, FL; www.htitech.com).

This simple analog approach has two key problems. First, pill calibration data must be tracked, since each pill has a unique calibration curve that relates received frequency to temperature. Second, these pills broadcast on a similar frequency, resulting in cross-talk among test volunteers in close proximity. Due to this potential for interference, pill receivers cannot be too sensitive, and only one sensor can be used on a give individual.

To address these problems, an improved microprocessor-controlled thermometer pill is being developed with US Army support. This new telemetry pill should be smaller, less expensive, easier to use, and more capable. In contrast to the current analog system, the new digital temperature sensors will broadcast actual temperature and a unique identifier, making it possible to use multiple skin and core temperature sensors on a given individual (Mini Mitter, Inc., Bend, Oregon; www.minimitter.com).

In the present study, heart rate (HR) was derived electrocardiographically using adhesive electrodes. Over more extended periods of wear, approaches using methods that do not involve adhesive electrodes or potentially uncomfortable chest straps would be more appropriate.

Personal Area Network (PAN)

The ability to connect a variety of body-worn sensor through a PAN is particularly critical for combat casualty care activities such as remote wound detection, remote life sign detection, and remote triage. A successful PAN must be comfortable, low power, lightweight, and not produce electromagnetic signatures that can be used to detect the location of the wearer. Furthermore, PANs must be rugged, reliable, compatible with a variety of garments and body worn equipment. However, this level of functionality is difficult to achieve in field environments where power, weight, and bandwidth are limited, and operating conditions are often harsh due to vibration, shock, immersion, and temperature extremes.

In the present study, sensor data was routed via a PAN to a central data processing point, or hub, where digitized data was stored and re-transmitted via off-body telemetry (Model DRG-115; Freewave Technologies, Boulder, Colorado; http://www.freewave.com). The PAN used commercial components (model TR3001; RF Monolithics, Inc., Dallas, Texas; http://www.rfm.com) to push data to a central hub. That is, the sensors periodically and redundantly transmitted data to the hub receiver. Collisions between data packets occurred, but the slow data rate needed to monitor HR and Tcore changes allowed this simple approach to succeed. This PAN is typical of most other existing PAN technologies - that is, somewhat primitive and based on an ad hoc design that has a tendency to be brittle and error-prone. Alternate approaches using wired PANs risk snagging or connector failure and tend to restrict sensor and processor placement. Wireless RF PANs, such as Bluetooth, are detectable at ranges of 10 km by electronic intelligence systems and yet may be locally unreliable due to blockage by the user's body. Alternatives to wired and conventional RF PANs, such as short-range PANs using free space magnetic induction and inherently short range propagation and low power consumption, have yet to be explored.

Beyond basic hardware issues, there is an enormous gap in our toolkit of software techniques for constructing such systems, particularly with respect to reliability, dynamic reconfiguration, and intelligent data management in low-bandwidth and limited storage situations. Given inherent PAN bandwidth constraints, innovative approaches to data management in the network will be a crucial technology for achieving scalability in this type of system. Such technologies would address issues of data storage and retrieval as well as the management of data flow through the network. We will have more to say about these problems later.

Data Management

Managing large time series data sets quickly and effectively can be nettlesome and time consuming. This is consistent with Lewis's point of view (10) that the "bottle neck" in scientific production is not the basic science, but the ability to deal effectively with the data. The approach of manually formatting and merging data files, and writing ad hoc software to process new and different file types was too time consuming. To solve this problem, we characterized the various data types, organizing these data types into a comprehensive archive, and developed simple yet powerful software routines to access subsets of data. This automated approach depends on two elements: a standardized representation of data, and software tools that use this representation to quickly view and export selected data for further analysis.

<u>Data standardization</u> - Typical field study data includes an array of data types - ranging from weather to clothing characteristics to physiologic data (Table 1). The exact characteristics of field data sets varies from study to study.

Table 1. Typical field study data types, sampling intervals, and data persistences.

Data Type	Collection Interval	Data Persistence
Core Temperature	**1 min**	**Instant**
Heart rate	**Beat-to-beat**	**Instant**
Geo-location	**2 sec**	**Instant**
Meteorologic	**15 min**	**15 min**
Clothing log	**60 min**	**60 min**
Equipment log	**60 min**	**60 min**
Video	**Sporadic**	**Length of clip**
Photographic	**Sporadic**	**Instant**
Activity log	**60 min**	**60 min**
Weight	**24 hour**	**24 hour**
Biographic	**Once**	**Study**
Comments	**Sporadic**	**Instant/range**

In spite of the variety of data types, automated data analysis was possible given that the formats of all the data were known. However, the challenge was to develop generally useful data analysis tools that could be used when the number and types of sensors changed, and new research questions resulted in new types of data queries.

Data Characterization. Most data archiving schemes are based on known schema. These schema are captured in a standard data model such the relational model, object/relational models (2, 4, 10, 11, 21), flat file schemes (2, 6, 10, 11, 21), hierarchical data models (21), and hybrids (2). Each model has its advantages and disadvantages for archiving data but none addressed the fundamental problem of organizing sets of data with unspecified structures. In the current implementation, the flat file method of archiving data seemed to offer the most promising route for organizing such an extensible data set.

The flat file method had been used with some success in certain bibliographic and complex protein sequence databases (1, 5, 6). The use of tagged data items and ASCII text in these databases offer many advantages. Tagging data means that a loose file structure can be maintained, new types of data can be added without compromising the data archive, and data are readily accessed by investigators (6). Tagging of data is not new and has been employed in the Standard Generalized Markup Language (SGML), an international standard (9, 20) widely used for document management. A subset of SGML called extensible markup language (XML) is

commonly used for data sharing between businesses, and is increasingly being used by the World Wide Web community. The XML format was a natural choice for an extensible and standardized way of representing our field study data streams.

The problem of encoding data within XML was first approached by examining and enumerating both the types of data, and the types of questions to be addressed by the data. Secondly, the data types were abstracted and broken down into key components. Through this process, five identifying properties were found to characterized each data point: location, time, temporal persistence, to whom or what the data related, and what the data represented. These five properties allowed the data to be represented by three key axes - space, time, and entity - on which data can be collapsed or expanded.

Relational Database Systems are notoriously bad at handling time-series data. To help address these time series data management problems, a prototype Data Visualization/Data Mining tool (DVDM) was developed to read and mine (extract data) from time-series XML data archives. The DVDM tool is generic and generally usable as long as data are represented as objects within the XML format. Context as to what the experimental data measure is provided by the experimenter. The tools is based upon time granulizing all data, and resolving what data exist or are valid for a given time granule. The software also allows users to select the preferred method of dealing with multiple data points within a time granule. Entity-to-data relationships are also resolved. Thus data can be viewed and collapsed by time slice and entity (subject). Queries can also be made on any type of data, and multiple queries can be stacked. The DVDM also allows queries across time, and once pertinent periods of time are identified, data can be exported for further analyses by statistical, graphical, and other analytical tools. Although the DVDM will work with any time resolution, the amount of data that can be analyzed at a given time is limited by the working memory (RAM) of the computer being used.

Results

The following figures show meteorologic data, and physiologic data collected in real-time from six male soldier (age = 22±4y [mean±SD]; ht = 172±5 cm; wt = 69.3±11.6 kg; %body fat = 13.9±6.9; load carried = 19.0±2.9 kg) during a simulated attack on the McKenna Military Operations in Urban Terrain (MOUT) facility at the Dismounted Battlespace Battle Lab, Ft. Benning, Georgia. Meteorologic conditions were temperate (Figure 1) with an estimated WBGT (wet bulb globe temperature) of only 19 to 23 ^{o}C. The WBGT was estimated from air temperature, relative humidity, and solar radiation (14).

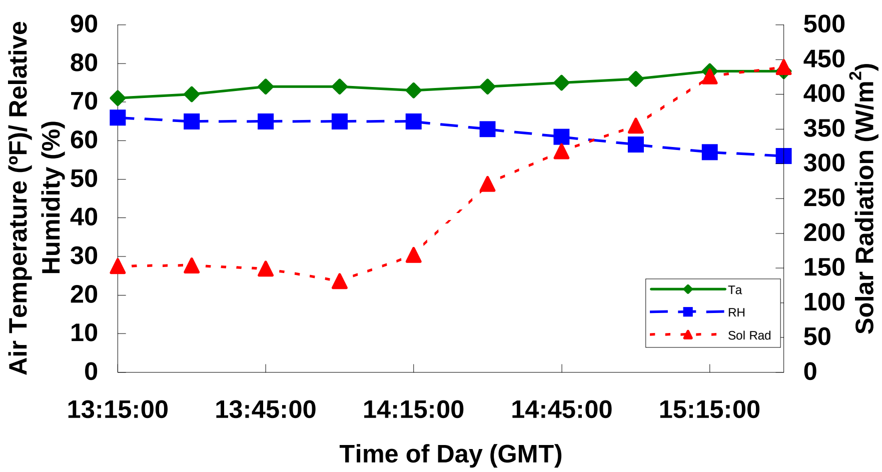

Figure 1. Meteorological conditions (air temperature, relative humidity, solar radiation) during the simulated attack in an urban setting.

The mission consisted of a simulated attack by a squad of soldiers on an opposing force ensconced in the single and multi-story buildings of the McKenna MOUT facility at the Dismounted Battlespace Battle Lab, Ft. Benning, Georgia (see http://192.153.150.25/dbbl/dfd/mkenins.htm). All soldiers were equipped with MILES (Multiple Integrated Laser Engagement System). The general route of the attack within the McKenna MOUT facility is shown in Figure 2. Changes in Tcore, heart rate, and PSI during the simulated attack are shown in Figures 3 to 5, respectively.

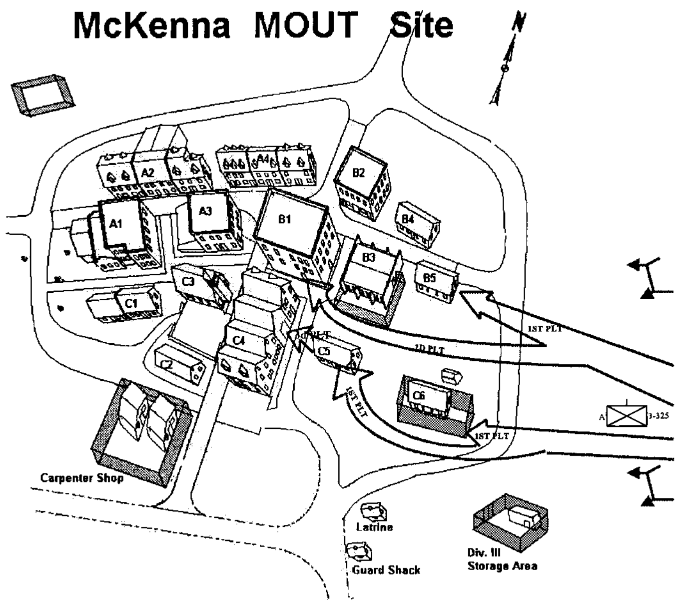

Figure 2. Arrow show the route of the simulated attack at the McKenna military operations in urban terrain (MOUT) training facility.

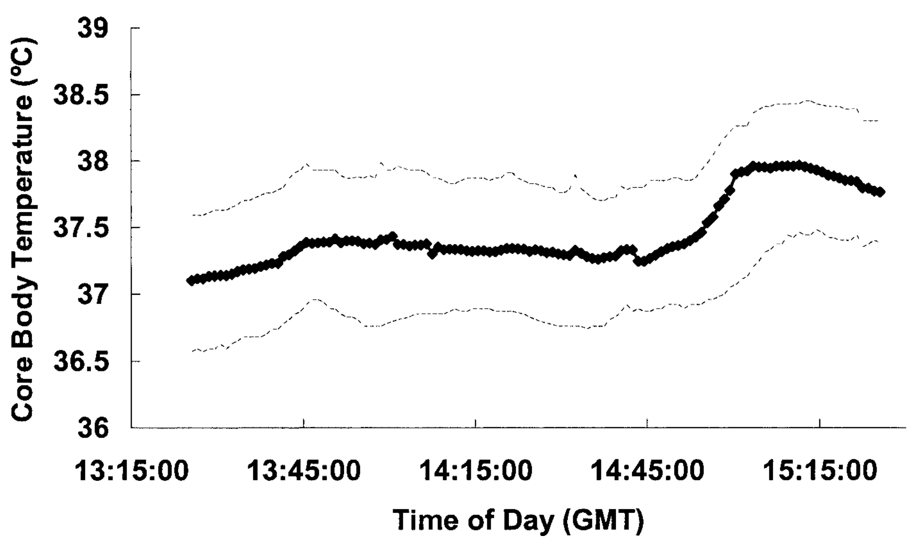

Figure 3. Core temperatures (mean ± range) as measured by ingested telemetry pill and monitored in real time during a simulated attack at the McKenna military operations in urban terrain (MOUT) training facility.

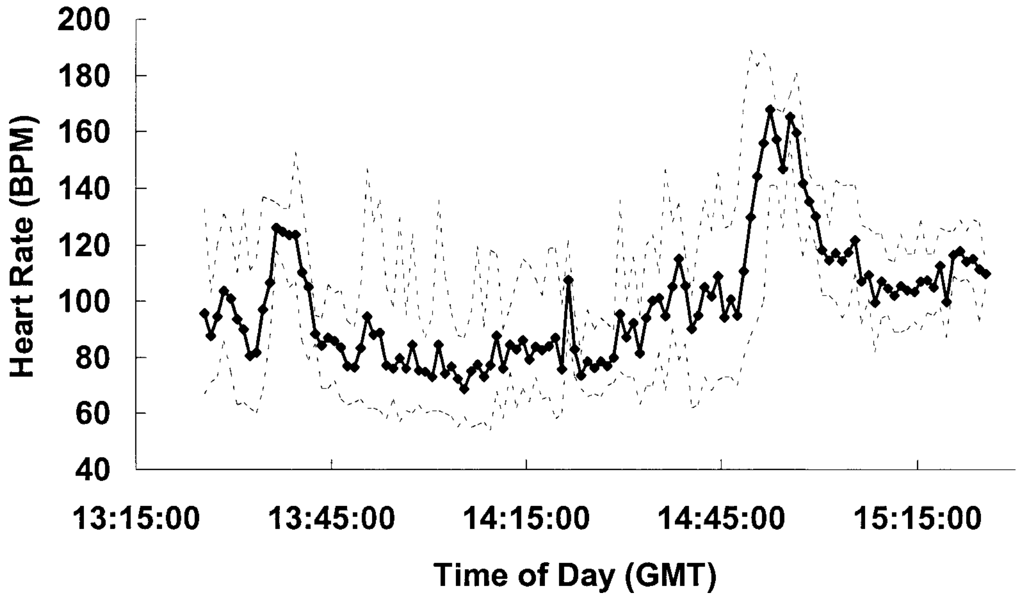

Figure 4. Heart rate (mean ± range) by electrocardiogram and monitored in real time during a simulated attack at the McKenna military operations in urban terrain (MOUT) training facility.

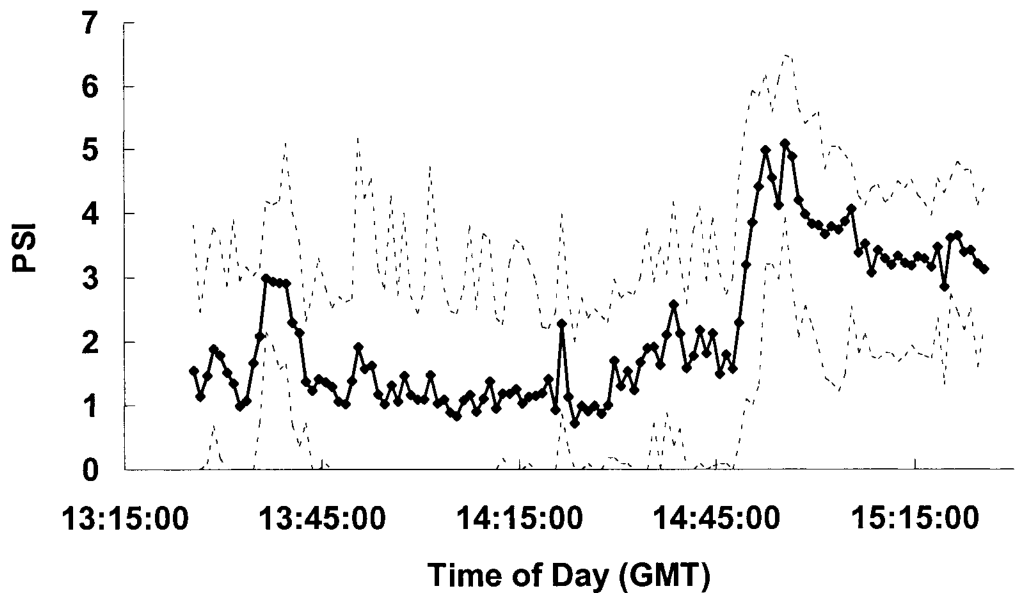

Figure 5. Physiological strain index (PSI) (mean ± range), calculated from heart rate and core temperature, during a simulated attack at the McKenna military operations in urban terrain (MOUT) training facility.

The PSI data was transmitted to and displayed at the control center of the MOUT training facility. Although the soldiers were equipped with wearable computers (Xybernaut Corporation, Fairfax, Virginia; http://www.xybernaut.com), technical problems prevented transmission of the PSI data to the soldiers. Instead, the squad leader intermittently viewed PSI data and other tactically useful sensor data by entering the control facility (PSI data from the less physically active squad

leader is not presented). The current and historical PSI for each individual soldier was displayed in the control facility (data and data display are on USARIEM's web page **http://www.usariem.army.mil/wpsm/demo/wpsmview.html**). However, it seems that physiologic data that helps soldiers avoid becoming environmental casualties would be most useful locally, that is, to the individual soldier, the squad leader, or the platoon medic. The relatively wide range of PSI among the soldiers probably reflects individual differences in tasks being performed, load carried (16 to 24 kg), and differences in heat acclimation and physical fitness - two factors that significantly affect tolerance of heat stress (17). The slow decline in PSI post mission suggests repeated bouts of exercise could lead to thermal strain even under temperate conditions.

Discussion: The Need for a New Approach to Data Management

Data management has long been the province of database management systems (DBMSs). Modern DBMSs are quite impressive when dealing with huge amounts of data with very regular structure; however, they are not as well suited to less predictable environments that are dominated by time-series data. They were not built with time-series data management as a goal, and as a result, the underlying access methods were designed to support set-at-a-time processing as is represented by the SQL (12) query language. Structuring the underlying database and forcing SQL to work efficiently with temporal data is a difficult if not at times impossible process (19), with simple time-series operations such as time-based merging, interpolation, extrapolation, and time-based aggregates (e.g., windowed average) being unsupported.

On the other hand, it is our strong belief that sound principles of data management can be successfully applied to setting such as ours to achieve high-performance in the face of resource restrictions. Given the complexities of the sensor-based environment, it is difficult to see how a more extensive and less controlled deployment could succeed without a reasoned approach to the intelligent management of physiological data. We are beginning to investigate the proper structure for a data management infrastructure that will allow for extensible, reliable, and scalable processing of sensor data. This study involves identifying the appropriate software primitives and a workable software architecture for tying them together. We aim to design primitives that can be used at all levels of the sensor network - from the sensors themselves and the local soldier-based processing hubs, up to and including the centralized archiving facilities.

Sensors produce ordered, append-only data structures that we will call *streams.* These streams must be produced by filtering, aggregating and combining sensor data as it is generated. The processing of multiple input streams can be expressed as a query that is analogous to a query written in SQL for relations. Processing requirements expressed as a query allow the system to apply optimization techniques. One of the major differences between our system and a standard DBMS is that streams must be processed as new data items are produced. The answer to a stream query is always evolving. Queries of this kind have been called *continuous queries* (3) since they are continuously evaluating their inputs. Continuous queries over time-series data (streams) will be a key part of a data management facility that can dynamically adjust its processing strategies to best fit the current demands of the network.

Data management is typically driven by careful assessment of application needs. For the DBMS, this is done by a Database Administrator (DBA) who is responsible for understanding possibly conflicting application requirements and for tuning the DBMS accordingly. In a highly dynamic and large-scale environment, this approach is not feasible. Instead, the users and/or the applications must pre-declare their data requirements along with their relative priorities. Such declarations are called *profiles*. In particular, a user's profile should be able to specify characteristics of the individual that might affect the way in which data is collected and moved

through the PAN. For example, if a user were known to have a propensity for heat injury, PSI monitoring would be given a higher priority.

Based on these profiles, the system can make data management decisions that use available resources for the maximum benefit. For example, more important items can be scheduled for transmission before less important items, data reporting rates can be reduced when no application needs higher ones, and caching can be used to decrease retrieval latency of popular items.

The combination of stream-based queries with a sophisticated application profiling facility provides the conceptual framework on which a data management substrate can be built. This substrate can automatically adjust its processing strategies (optimization) with respect to how the system uses cache space, orders the delivery of information, sets appropriate data rates, and chooses the most efficient algorithms for the evaluation of queries. It will also be able to make intelligent choices about how sensor data should be stored in order to support efficient future retrieval.

Conclusions

- This study suggests physiological monitoring could be used to reduce environmental injuries among soldiers. Specifically, near real-time monitoring of PSI could be used to reduce the incidence of heat injuries in military operations where work/heat strain is a significant risk.
- Remote physiological monitoring is also needed to support remote combat casualty care activities such as remote wound detection, remote life sign detection, and remote triage.
- However, significant sensor, PAN, and data management and modeling work remains to be done before the routine collection, dissemination, and use of physiologic information is practical for the dismounted soldier.

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Disclaimer

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Improvement of the U.S. Army Intermediate Cold Wet Boot

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Summary

In 1988, the U.S. Army began a program to develop a new combat boot for dismounted soldiers and marines operating in cold and wet environments where the mean monthly temperature ranges between -10° and +20° C. The new Intermediate Cold Wet Boot (ICWB) was designed to fill the protective void between the uninsulated U.S. Army Standard Combat Boot and the highly-insulated U.S. Army Extreme Cold Weather Vapor Barrier Boot. The development of the ICWB has been managed under a unique U.S. Army Pre-planned Product Improvement (P^3I) program that is designed to continuously improve the protective performance of the boot through the rapid integration of proven technological advances in design, fabrication, and materials. Since 1991, numerous changes have been made to the ICWB under this dynamic P^3I process. These include improvements to the boot's outer leather, insulation, waterproof/breathable membrane, insole, and midsole as well as other enhancements to the structure of the basic boot. Since the boot's inception, the Biophysics and Biomedical Modeling Division of the U.S. Army Research Institute of Environmental Medicine has been responsible for extensive biophysical and physiological evaluations of current and prototype versions assessing the potential impact of new technologies on the environmental protective capabilities of the ICWB. The continuous adaptation of improved features to the ICWB has resulted in a boot with a high degree of wearer acceptance within the U.S. military and could serve as a model for future protective clothing procurement by other NATO countries.

Introduction

Every major military conflict since 1700 has recorded the failure of personal equipment issued to combat troops to perform as required. Historical literature from these campaigns is replete with documentation of infantry troops suffering significant losses from the inadequacies of their military-issue protective clothing, especially footwear (1-5).

Military campaigns conducted during periods of prolonged cold-wet weather have usually resulted in a high incidence of non-freezing cold injury (NFCI) to the feet of ground troops wearing footwear incapable of providing sufficient protection relative to the combat theater. During World War II, 87% of all U.S. military cold-induced injuries were incurred by front line infantrymen and in many cases the combat effectiveness of entire infantry units was nullified (1). Furthermore, the effects of combat-induced cold injury in World War II prevented all but 15% of casualties from returning to active duty (1). The high incidence of NFCI (i.e.,"trenchfoot") to the feet of infantry troops in both the Mediterranean and European Theaters of World War II compelled the U.S. Army to initiate a research program aimed at developing footwear that would minimize these types of injuries. This research continues today and is reflected in the development of the footwear system described in this paper.

Cold-induced injury to the human foot has a relationship to the physical environmental factors (i.e., temperature, altitude, precipitation, wind velocity, thawing, terrain, and shelter) in the proximity of the combat theater. NFCI involving the feet can cause recurring circulatory problems and extreme cold sensitivity in many patients. Trenchfoot is characterized pathologically by circulatory, neurologic and sudomotor changes which are expressed by local tissue damage and sterile inflammation. Because the

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condition affects both nerves and blood vessels, the first sign is loss of sensation in the toes followed by swelling of the foot resulting from rewarming during medical treatment. The foot is sensed to be hot, appears red in color and the swelling can be so great that it is impossible to redress the foot with a boot. The pain which follows is unremitting and is often unaffected even with the use of morphine. A prolonged exposure can result in gangrenous tissue requiring amputation. Whayne and DeBakey reported that numerous soldiers who sustained NFCI to the feet during World War I (1918) were still under the medical care of the Veterans Administration as late as 1949 (1). Despite extensive materials research advances since 1945, many of the longstanding problems associated with the development and eventual procurement of effective military footwear for cold-wet winter use still remain to be resolved.

A large number of infantry troops from the United Kingdom suffered from NFCI while engaged in a 25-day campaign of continuous combat during a traverse of East Falkland Island during May-June, 1982 (6). The prevailing weather during the ground operations was described as classical cold-wet conditions with daily temperatures averaging 0^{o}C, persistent rainfall, and high velocity winds (7).

In 1988, the U.S. Army began development of a new combat boot for dismounted soldiers operating in cold and wet environments. The Intermediate Cold Wet Boot (ICWB) was designed to fill the void between the Standard Combat Boot and the Extreme Cold Weather Vapor Barrier Boot. The ICWB is actively managed under a unique Pre-planned Product Improvement (P^3I) program designed to continuously improve performance through rapid integration of proven technological advances in design, fabrication, and materials.

Since the boot's inception, USARIEM has been responsible for biophysical and physiological evaluations of current and prototype versions to improve the environmental protection provided by the ICWB. Other U.S. military researchers have also made a multitude of material and structural changes to the upper, insole and outsole of the boot. This paper documents over a decade of USARIEM research assisting in the continued improvement of the ICWB.

Biophysical Testing

To date, 46 different prototype boots have been evaluated by USARIEM in a continuous effort to improve the environmental protective capabilities of the ICWB. Test boots have ranged from modified military boots to a variety of commercial outdoor products. Initially, a 1988 market survey produced a boot design that was 26 cm high with a water resistant leather upper, waterproof/breathable protective membrane, synthetic insulation, and lugged rubber outsole. In 1989, 4 military and 7 commercial boots were selected for intensive biophysical testing on the USARIEM Thermal Foot Model (TFM, Figure 1) to establish the thermal insulation range available from this type of footwear under various environmental conditions.

The TFM is a copper, life-sized model of the human foot that measures both localized and total thermal resistance, R ($m^2 \cdot K \cdot W^1$). Power input and the calculation of insulation values for the total foot model and its 29 individual sections are controlled by an automated system. The copper surface of the foot model is controlled at 30^{o}C. Regional thermal resistance (R_r) to heat exchange is calculated using

$$\mathbf{R_r = A_i \cdot T \cdot P^1}$$

where

A_i = area of each regional segment, m^2,
T = temperature gradient between the foot model surface and ambient air temperature, ^{o}C, and
P = regional power input, W.

Ideally, three separate samples of the test footwear system are evaluated and the average value is reported. R values can be converted to the more familiar clo unit (1 clo = 0.155 $m^2 \cdot K \cdot W^1$) to establish a ranking order of standard and prototype footwear for downselection and subsequent procurement purposes. The initial TFM testing also assisted in the selection of types of thermal insulation and protective membrane that were chosen for the ICWB.

The first ICWB fielded was close to the original design utilizing Thinsulate™ insulation, a Gore-Tex™ membrane, and a Vibram™ outsole. From the mid 1990's, USARIEM research efforts have

concentrated on reducing overall boot weight while expanding the protective temperature range of the ICWB. To accomplish these goals, extensive TFM testing was done to identify improved, lightweight insulation materials and the optimal amount of insulation the boot could functionally accommodate.

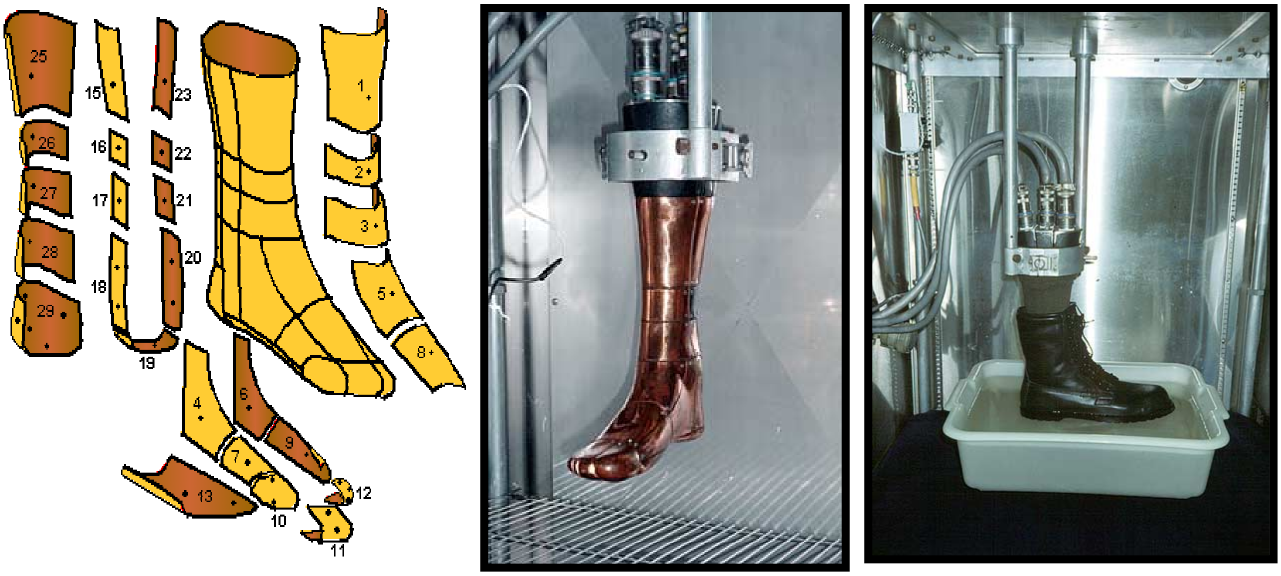

Figure 1. Photographs of the USARIEM Thermal Foot Model (TFM) showing the 29 individual zones (left) and the method of evaluating military footwear for thermal resistance when exposed to external moisture (right).

In 2001, TFM testing assisted in the decision to make a major modification to the ICWB by allowing the insulation to be removable in the form of a separate bootee liner (Figure 2). Personnel will be issued two pairs of bootees and will be able to quickly exchange wetted bootees with dry replacements. This latest version of the boot has a more waterproof leather upper with the Gore-Tex membrane bonded to the inner surface. Changes have also been made to the boot's tongue with upgraded leather and the entire rubber midsole has been replaced with softer, more flexible polyurethane.

Figure 2. Photograph showing the latest version (2001) of the ICWB with removable insulation liner.

Physiological Testing

In 1990 two commercial and three military boots (Figure 3) downselected from TFM testing were evaluated during controlled wear trials to define human thermophysiological responses at the extreme ends

of the ICWB temperature range (8). Early in the ICWB planning process, military planners were hopeful that an existing service boot could be configured or modified to provide the protection and performance required by the new boot.

Each boot was evaluated under two different scenarios conducted on two consecutive test days. On the first day all test volunteers wore a new pair of the same type boot and attempted to sit for 240 min at an ambient temperature (T_a) of -23.4°C, dew point temperature (T_{dp}) of -34.7°C, and an air velocity (V_a) of 1.7 $m \cdot s^{-1}$ (SIT, Figure 4). This scenario was designed to simulate static military situations such as enemy contact, sentry duty, bivouac, etc. After SIT, the boots were immersed upright in 8 cm of water for approximately 17 h. Subjects donned the same pair of boots and attempted a treadmill walk for 60 min at 1.34 $m \cdot s^{-1}$ followed by sitting for 60 min at T_a=-1.0°C, T_{dp}=-9.4°C, and V_a=1.4 $m \cdot s^{-1}$. This scenario was then repeated for 240 min total exposure (WALK/SIT). It was designed to simulate the effects of a prolonged traverse over wet terrain and observe potential foot cooling caused by wearing wet boots during periods of inactivity. Individual rectal temperature, skin temperature, and heart rate were recorded every minute during the experiment.

Volunteers wore the U.S. Army Extended Cold Weather Clothing System (ECWCS). The ECWCS utilizes the "layered" concept of insulation which is intended to minimize the chances of excessive overheating or rapid cooling by either removal or addition of appropriate system components according to the operational environment. The system consists of four inner layers of synthetic, hydrophobic garments and an outer layer of GORE-TEX-lined parka and trousers. The ECWCS has a thermal resistance, R_c ($m^2 \cdot K \cdot W^1$) =0.56 and a water vapor resistance, R_e ($m^2 \cdot kPa \cdot W^1$)=0.082 when measured on a thermal manikin. All subjects wore a U.S. Army Standard Arctic Mitten Set (R_c=0.37 when measured on a Thermal Hand Model). Total weight of the system less footwear and handwear was 10.1 kg.

Boot 1. Standard-issue U.S. Army Cold-Wet Vapor Barrier Boot, all-rubber construction, wool-felt insulation, 2.89 kg/pr., 26 cm high over the U.S. Army Cushion Sole Sock (Control Boot).

Boot 2. Modified U.S. Army Cold-Wet Vapor Barrier Boot, all-rubber construction, THINSULATE®[2] insulation, 2.49 kg/pr., 30 cm high over the Cushion Sole Sock.

Boot 3. Rocky model #7017, all-leather boot, GORE-TEX®[2] membrane, THINSULATE insulation, 1.77 kg/pr., 25 cm high over the Cushion Sole Sock.

Boot 4. Cocoran model III, all-leather boot, SYMPATEX®[2] membrane, THINSULATE insulation, 2.5 kg/pr., 25 cm high over the Cushion Sole Sock.

Boot 5. Multi-Component Boot System (MCBS), 1.9 kg/pr., 25 cm high, consisting of the U.S. Army Leather Combat Boot over a separate GORE-TEX sock, the U.S Army Ski Mountain Sock, and a thin polypropylene sock.

Figure 3. Physical description of test footwear systems tested during the 1990 physiological test.

In 1998, a second human physiological evaluation was conducted to assess the potential of new microencapsulated phase change materials as a replacement for the Thinsulate insulation currently used in the ICWB (9). These new lightweight insulating materials, purporting to absorb and release body heat through a phase change process have recently appeared on the commercial outdoor clothing, handwear, and footwear markets (10). A phase change material (PCM) can be defined as any material that has the ability to readily absorb and reject heat. Current manufacturing processes allow for specific transition temperatures at which point the latent heat of fusion of the PCM is either absorbed or rejected. For footwear insulation applications, PCM are microencapsulated and then integrated into foams or fibers that are incorporated into the lining of the boot. Encapsulation ensures that the phase change process can be continuously repeated without loss of any PCM. The PCMs evaluated in this study were specifically engineered by the manufacturers to improve the thermal comfort of the human foot during exposure to cold ambient temperatures.

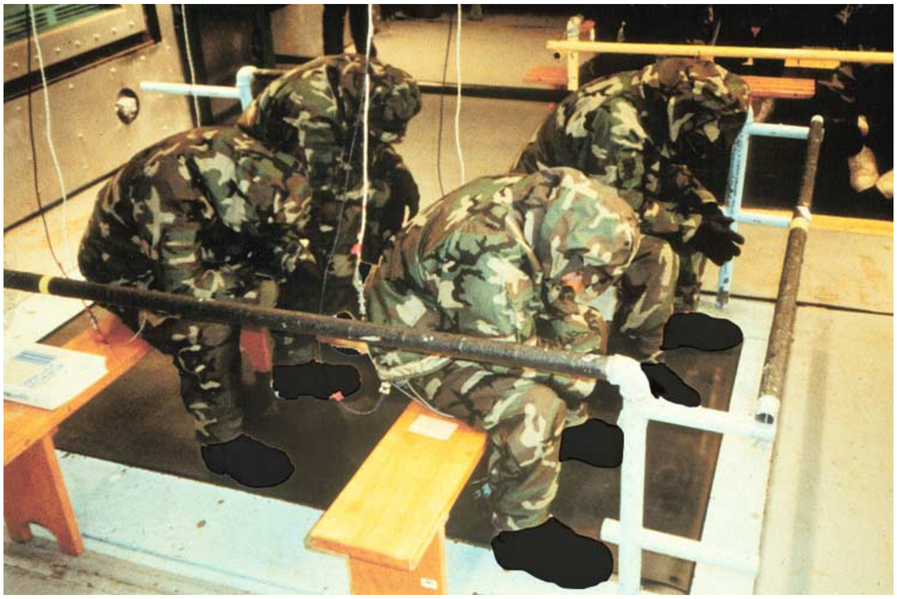

Figure 4. Photograph showing human volunteers during the 1990 ICWB physiological climatic chamber testing.

Eight volunteers wore a modified version of the ECWCS and a new pair of the test boots each day. The basic experiment consisted of walking on a level treadmill for 15 min at 1.34 $m \cdot s^{-1}$, followed by sitting still on a wooden bench for 70 min at 0°C and at -12.3°C. Temperatures of both small toes, both big toes, rectal temperature, and a 3-point mean weighted skin temperature were continuously recorded. Prior to human testing, all four test boots were evaluated for both overall and toe region thermal resistance. The four boots tested were the 1996 standard U.S. Army Intermediate Cold Wet Boot (Control), insulated with 3M Thinsulate™ and three boots identical to the control but insulated with different PCM: Frisby Technologies ComforTemp™ (Boot 1); Gateway Technologies Outlast No. 8088™ (Boot 2); and Outlast Cortina™ (Boot 3). Table 1 describes the test boots in detail regarding identification, physical location, and manufacturer of all protective materials.

Table 1. Identification and physical location of protective material layers for all test boots.

	Foot Skin Surface →	→ →	→ →	→ Boot Outer Leather
Control Boot	Cambrelle	200 g Thinsulate	Gore-Tex	200 g Thinsulate*
Boot No. 1	Cambrelle	ComforTemp Foam	Gore-Tex	200 g Thinsulate*
Boot No. 2	Cambrelle	Outlast No. 8088	Gore-Tex	200g Thinsulate*
Boot No. 3	Eclipse 200S	Outlast Cortina	Gore-Tex	200 g Thinsulate*

ComforTemp™ phase change foam manufactured by Frisby Technologies, Clemmons, NC USA.
Outlast™ No. 8088 and Cortina™ microencapsulated phase change materials manufactured by Gateway Technologies, Boulder, CO USA.
Thinsulate™ microfilament polyester polyolifin manufactured by 3M Corp., St.Paul, MN USA.
Gore-Tex™ laminate material manufactured by W.L. Gore and Associates, Elkton, MD USA.
Cambrelle™ lining material manufactured by Faytex Corp., Weymouth, MA USA.
Eclipse™ lining material manufactured by Tempo Shain Corp., Salem, MA USA.
*This layer of Thinsulate was located in the upper shaft area only in all test boots.

Results

Since 1988, TFM testing of ICWB prototypes has shown that these types of boots have a range of insulation between 0.210 and 0.330 $m^2 \cdot K \cdot W^{-1}$. Through the TFM testing process, the current version of the ICWB has been modified to contain the optimal weight of Thinsulate insulation (200 gram), has had the Gore-Tex membrane repositioned to the inner surface of the upper and now has the entire insulation package redesigned as a removable bootee.

Table 2 shows overall and localized thermal resistance values from the TFM for the test boots used in the 1990 physiological study. Values given are for dry boot/sock combinations and after an 18 hour immersion in shallow water which effectively simulates a prolonged exposure to wet terrain conditions. Table 2 also shows that boot nos. 3 and 4, utilizing a permanent, internal waterproof/breathable membrane incurred large reductions in overall thermal resistance as a result of an 18 h immersion in 10 cm of water. The water level during immersion was sufficient to cover the entire welt and any adjacent stitching of all test footwear. Similar reductions were also observed in the three toe regions (nos. 10, 11, and 12) that are initial anatomical sites for NFCI. Both boots allowed for the ingression of small amounts of standing water after the immersion. The reduction of thermal insulation due to water ingression can have an immediate impact on wearer comfort as well as subsequent susceptibility to NFCI (11). Boot nos. 1 and 2 that utilized a vapor-barrier (VB) had minimal reductions in thermal resistance as a result of the water immersion and were dry internally after the immersion tests. Boot no. 5 which also utilized W/B in the form of a separate, removable Gore-Tex sock had moderate losses of insulation after immersion. The leather used in the construction of the boot was developed for increased water resistance and allowed no observable water ingression during immersion.

All boots increased in total weight after immersion. The smallest average increases per boot pair was with boots 1 (26 g) and 2 (42 g). Boots 3 (196 g), 4 (444 g), and 5 (147 g) absorbed substantially larger amounts of water.

Table 3 shows that no volunteer was able to endure the desired 4-hour exposure when wearing any of the test footwear while inactive at-23.4^{o}C. Both of the well-insulated, rubber VB boots provided marked increases in ET compared to the three less insulated, leather boots utilizing waterproof/breathable membranes. Analysis of variance (by repeated measures) indicated an overall significant effect of boot type on ET ($F= 29.78$, $p= 0.0001$). Further analysis using Tukey's Studentized Range Test revealed significant differences in ET (boot 1 > boots 3, 4, and 5), (boot 2 > boots 3, 4, and 5). All exposures (n=39) were premature due to either voluntary termination by the volunteer as a result of thermal discomfort or a toe temperature measurement reaching predetermined safety limits.

This 1990 human evaluation indicated that only vapor barrier-style military footwear was capable of providing adequate foot protection in simulated cold wet conditions. The three all-leather boots, although utilizing protective membranes claiming to be totally waterproof and vapor permeable, failed to prevent absorption and/or ingression of large amounts of water into the boot after a protracted immersion in shallow water. TFM evaluations indicated that these boots would provide less protection when worn dry and post-immersion. The two vapor-barrier boots afforded increased thermal protection but were not recommended as the new ICWB because they are heavy, awkward to use, and cause the feet to sweat excessively during exercise. Without the implementation of a rigid program of foot hygiene including frequent sock changes, washing and drying of the feet, etc., the potential for maceration of the skin is greatly increased. Furthermore, if the rubber outer shell of a vapor-barrier boot is accidentally punctured by the use of skis, crampons, ice axes, etc., moisture ingression will quickly degrade thermal insulation.

These results prompted U.S. Army footwear developers to intensify their efforts to design an all-new ICWB with much improved waterproof capabilities including treated leather uppers and better waterproof/breathable membrane inserts.

Table 2. 1990 human test footwear-overall and toe region thermal resistance values ($m^2 \cdot K \cdot W^1$) measured on the Thermal Foot Model when dry and after 18 h immersion in 10 cm of water.

	Overall boot			Toe sections		
	Dry	Wet	% change	Dry	Wet	% change
Boot no.						
1	0.283	0.270	-0.05	0.346	0.313	-0.10
2	0.325	0.304	-0.06	0.366	0.313	-0.15
3	0.246	0.179	-0.27	0.234	0.152	-0.35
4	0.241	0.156	-0.35	0.246	0.144	-0.42
5	0.213	0.185	-0.13	0.204	0.160	-0.22

Table 3. 1998 human test-mean endurance time (ET, maximum=240 min) of volunteers wearing five candidate Intermediate Cold-Wet Boots while sedentary (T_a=-23.4°C).

Boot	1	2	3	4	5
ET (min)[a]	125	124	64	81	73
SD	23.7	21.2	17.7	19.7	14.0
Range	103-162	94-165	50-106	65-122	52-95
N	8	7	8	8	8

[a]There was a 51% incidence of premature attrition due to voluntary termination as a result of subject discomfort and a 49% incidence due to T_{sk} (toe) ≤ 5°C.

Table 4. 1998 human test footwear-thermal resistance values (R, $m \cdot K \cdot W^{-1}$) for the overall boot, for toe sections only, and weights (kg) for all test boots.

	Overall-dry	Overall-wet	Toes-dry	Toes-wet	Weight-dry*	Weight-wet*
Control	0.242	0.208	0.233	0.161	1.01	1.12
Boot No. 1	0.237	0.205	0.240	0.167	1.11	1.26
Boot No. 2	0.231	0.205	0.225	0.161	0.99	1.10
Boot No. 3	0.239	0.215	0.233	0.167	1.01	1.11

All dry R values were means of 3 separate evaluations and wet R values from only 1 evaluation.
Wet R values calculated after Thermal Foot Model/test boot immersed upright in 10 cm of water for 18 h.
All boots were size 10 R and tested with the U.S. Army Standard Cushion Sole Sock.
*Weight of right-foot boot only.

Figures 5 and 6 show the time courses of mean small toe temperature during both environmental exposures from the 1998 human test. Time courses of mean big toe temperature displayed similar temperature trends and rank order of test boot/final toe temperature at the end of the exposure. During exercise at 0ºC, toe temperatures generally rose 3-4ºC in all boots while gradually declining during the following 70 min period when the volunteers were sedentary. In general, toe temperatures rose slightly during exercise at –12.3ºC while rapidly declining when volunteers were sedentary. Although mean final T_{st} and T_{bt} values were comparatively high with the Control boot in the 0°C environment, they were consistently

the lowest in the -12.3°C environment. Mean final T_{st} and T_{bt} values were highest in both environments when wearing Boot 1.

Thermal foot model results from the 1998 human test footwear showed that all boots were closely grouped in terms of dry and wet thermal insulation with no particular boot indicating that it would provide an increased level of thermal comfort. The then-current U.S. Army Intermediate Cold-Wet Boot,

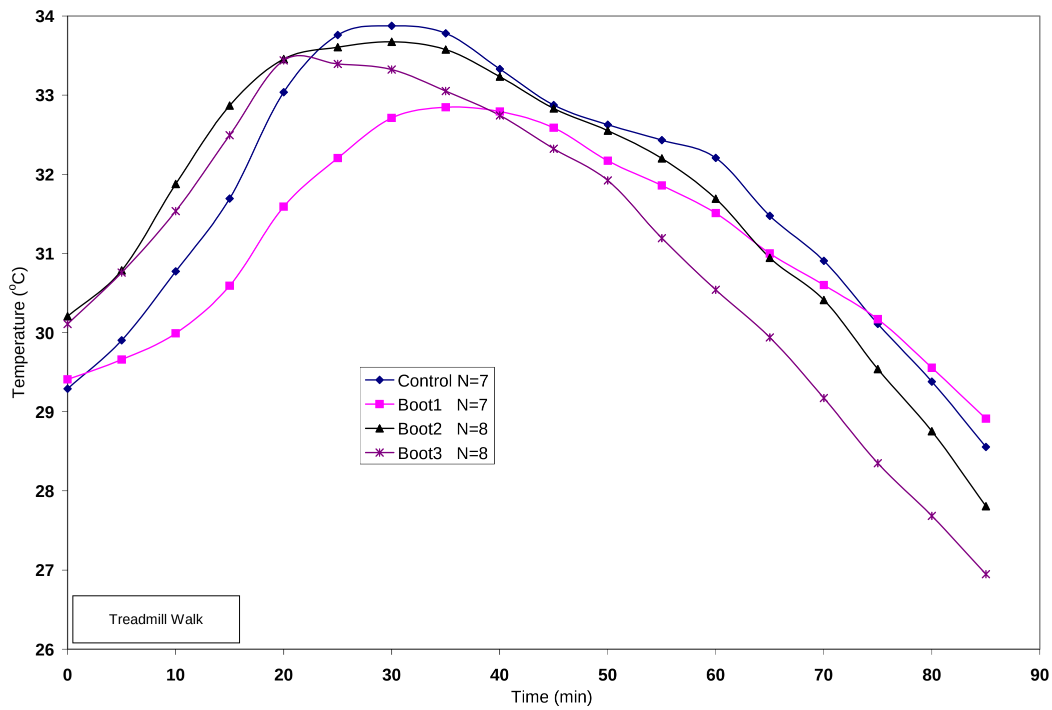

Figure 5. Mean small toe temperature for all test boots at 0° C.

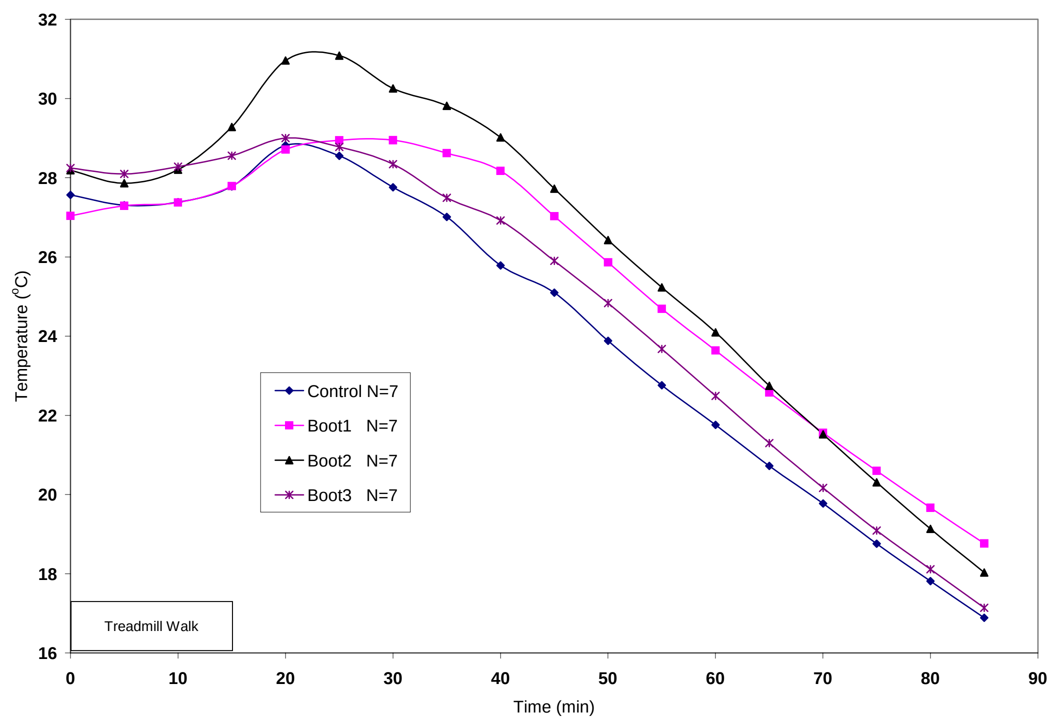

Figure 6. Mean small toe temperature for all test boots at –12.3° C.

issued to personnel operating in cold and wet environments, provided comparatively high toe temperatures at the upper end of the issue temperature range but was less effective at the lower end of the range. Finally, these results suggest that the phase change material in Boot 1 contributed to maintaining both cooler temperatures during exercise and warmer temperatures while sedentary at the skin surface of both the small and large toes. This could provide increased comfort and protection when worn during a more extended cold exposure.

Additionally, the general trend of the Boot 1 temperature curves showed that toe temperatures were cooler during exercise and warmer when volunteers were inactive. These trends also suggest that endurance time would be slightly longer with Boot 1 when compared to the other test boots if the cold exposures had been extended.

Although the current use of PCMs as boot insulation has been rejected, it has been recommended that the U.S. Army continue to evaluate future improvements in these materials designed to increase individual thermal comfort and protection.

Conclusions

The P^{3}I program, including the biophysical and physiological testing of prototype ICWBs has allowed U.S. Army footwear developers to field a boot which is regularly improved through the inclusion of proven technological advances. TFM and human volunteer testing has contributed greatly in the gradual evolution of the current ICWB. Comfortable, functional footwear is crucial to the success of military operations, especially those involving an extended exposure to cold and wet weather. The British Army's ground operations in the Falkland Islands War showed that a prolonged traverse over rough terrain during cold-wet environmental conditions by well-trained infantry forces wearing even "modern" combat footwear will result in a large percentage of soldiers suffering from serious cold injuries to the feet. Modern land warfare has the potential of being conducted at an increasingly rapid pace across a larger battlefield. Sustained military operations can result in infantry troops advancing far beyond sources of supply in order to achieve strategic objectives. Clean, dry clothing, socks and footwear will probably not be available when needed.

Continuous evaluation of new applications to improve the performance of the ICWB has resulted in an item that provides excellent cold-wet environmental protection along with a high degree of soldier acceptance. The active testing approach characterized by the P^{3}I program will ensure that the ICWB continues to evolve with the adoption of more effective technologies to maximize warfighter foot protection in cold and wet operational areas.

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The Steam Laboratory of the IMNSSA:
A Set of Tools in the Service of the French Navy

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Summary
Accidental exposure to hot water steam is a potential risk in the French Navy, and particularly on nuclear submarines or ships. Direct human exposure to this extreme environment during an accident leads to death in a short time.
In order to protect the crew members of the French Navy, a laboratory was created at the Institut de Médecine Navale du Service de Santé des Armées (IMNSSA). A set of tools was developed to study the effects of exposures to hot water steam atmospheres on human physiology and on protective capacities of textiles fabrics and equipments.

Introduction

Accidental exposure to hot water steam is a potential hazard in the French Navy and particularly on nuclear submarines or ships (Etienne et al., 1999).
To study the effect of human exposure to accidental steam atmosphere and in order to protect the crew members of the French Navy, a steam laboratory was created at the Institut de Médecine Navale du Service de Santé des Armées (IMNSSA). To carry out this study, a set of tools was developped: a testing device which can generate steam jets or steam atmosphere, a thermal copper manikin, a steam climatic chamber and a computer model of human thermal physiology.
The testing device allows to quantify the protective capacities of textile fabrics under steam stresses. The thermal manikin and the steam climatic chamber allow to evaluate protective capacities of equipments. The model allows to estimate the thermal strain due to the equipment and the environment.

Description of the materials of the laboratory

The testing device
The testing device can be used under two configurations : steam jet or steam atmosphere (Figure 1). It is composed by:

- a steam generator (Sano clav Wolf, Bioblock Scientific, France) which has a maximal inside temperature of 142°C, corresponding to a pressure of 3 bars. Steam is coming out from a copper tube (11 cm longer and 5 mm internal diameter) oriented toward the center of the measuring cell.
- a sample support composed by a PVC double frame in which the sample is inserted. The two sides of the frame present a circular window corresponding to the measuring cell diameter. The part opposed to steam is equipped to attach the measuring cell and to make a close contact between the cell and the internal side of the sample (supposed to face skin).
- a measuring cell (Figure 2) composed of a heat flux sensor (Episensor 025, JBMEurope, France) stuck on a hollow cylindrical box in which water circulates at a regulated temperature of 33°C. The side of the box facing steam (or the internal side of the samples) is made of an external resin layer (to minimise the radial heat flux) over an aluminium plate. The heat flux sensor, imbedded in the resin layer, is stuck on the aluminium plate to facilitate the transfer of the heat to the water. The sensor measures the heat flux and also the temperature of its surface under its external black paint layer.

Under steam jet configuration, the sample support and the measuring cell are fixed on a moving base. Under steam atmosphere configuration, this moving base is replaced by an isolated box in which steam atmosphere is created. In this configuration, the steam injection is made by an electrovalve asserved to a thermal regulator which regulates the box temperature at 80°C. In the two configurations, the measuring cell is

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connected to a data logger (DaqBook 216, IOtech, USA) and then to a computer that allows to observe and save the measures (software: Daqview 7.1, IOtech, USA).

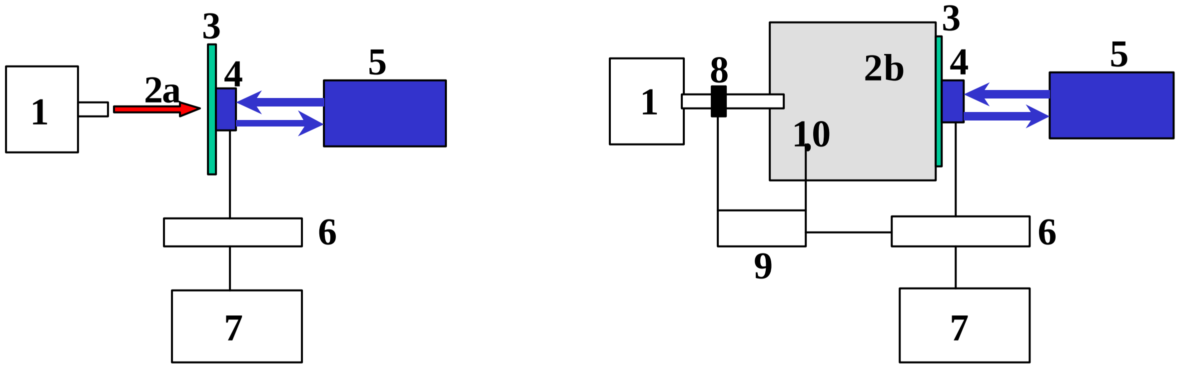

FIGURE 1 : Diagram of the testing device under steam jet (left panel) and steam atmosphere configuration (right panel). 1 : steam generator. 2a : steam jet. 2b : isolated box. 3 : textile sample. 4 : measuring cell. 5 : regulator of the water temperature of the measuring cell. 6 : data logger. 7 : computer. 8 : electrovalve. 9 : thermal regulator. 10 : temperature sensor.

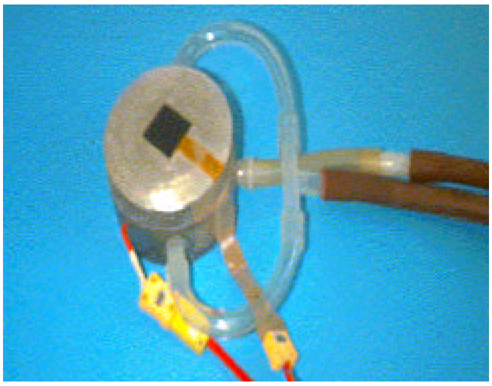

FIGURE 2 : The measuring cell, view of the sight facing steam or the internal side of the sample.

The climatic chamber
The climatic chamber (7 m^3) allows to generate a full saturated atmosphere of 80°C. The steam atmosphere is created by an air-conditioning (heating system and humidifier) working in close-circuit. Steam can be rapidely evacuated outside for security reasons.
The thermal conditions inside the chamber are regulated by a computer. Air and dew point temperatures are measured and stored on the same computer. The air temperature can be regulated between the air temperature of the laboratory and 90°C (± 1°C) and the dew point one between those of the laboratory and 80°C (± 1°C).
The copper thermal manikin
The thermal manikin is divided in nine separate segments. The surface of the manikin is made of copper sheets and is regulated by water circulated inside copper pipes distributed on the internal face of the sheets (regulated surface: 1.349 m^2). The inside of the manikin is isolated to limit heat storage and natural convection. This manikin presents two distinctive features compared to the majority of the other thermal manikins. It should be as watertight as possible and be cooled rather than warmed during the tests. The cooling system is composed by a primary input which is divided then in 3 secondary ones : one for the top (head, arms, front and rear trunk) and one for each leg, and then the water is distributed in the different segments. Each segment has a separate water output. The temperature of the primary input is regulated between 20.0 to 40.0°C (± 0.2°C), and the temperatures of the each segment are measured. The water flows are measured (Mc Milan Co, USA) and regulated at the output of each segment between 0.06 to 1.00 $l.min^{-1}$ (± 5%). Thus, total and local heat fluxes are calculated from temperatures and water flows.

The computer model of human thermophysiology « Protect »

« Protect » is a computer model of human thermophysiology created by Dr V Candas (CEPA/CNRS, Strasbourg, France) based on the Stolwijk model (Stolwijk, 1970) to which a model of heat transfer through clothing and a model of heart rate are added.

The input parameters concerne the climatic environment (air, radiant temperatures, relative humidity, air velocity and solar heat flux), the clothing and underwear (insulation, evaporative resistance, thickness, percent of body area covered …), the ventilation inside the garment (temperature and humidity of the air ventilated, distribution of the ventilation on the body surface), the potential human (height, weight) and his activity (metabolism, kind of activity).

The output parameters are temperatures of the garment, underwear and microclimate, internal and skin temperatures, sweat rates, dehydration, skin wettedness, heart rate.

Protect allows to realize scenarii composed of several trials having its own lasting. For each trials, all the input parameters can be changed.

Protect has been validated in warm to slightly hot climates with good agreement with measures (mean ± 2 SD) but not in steam atmosphere.

Testing procedures

Textile fabrics evaluation on testing device

Textile samples are exposed three times during ten minutes to four conditions of steam aggression (three conditions of steam jet and one of steam atmosphere). The Ref tests corresponds to the exposure of the measuring cell directly to steam aggression, without any sample. During Ref tests, the steam jet conditions lead to average heat flux rates of 43.12 (SD: 0.26), 33.94 (SD: 0.39) and 28.04 (SD: 0.33) kW.m^{-2}. During Ref test, the steam atmosphere (80°C, saturated) leads to average heat flux rate of 7.02 (SD: 1.17)) kW.m^{-2}. Heat flux and surface temperature of the flux sensor are measured throughout the test. Total amount of heat received by the cell over the ten minutes and the ratio between heat fluxes measured with samples and those of the Ref tests are calculated. The samples are classified depending on their physical properties and capacity to limit or modify the heat transfer under steam stress.

Equipments evaluation on manikin

Garments and equipments are exposed to steam atmosphere in the steam climatic chamber. The thermal manikin is worn with the equipment and placed in the center of the chamber. The climatic conditions are 80°C of air temperature with step increase of humidity to the maximum allowed by the equipment. Due to high level of condensation on the regulated surface of the manikin, the chamber cannot reach saturation when the manikin is in. Thus, humidity is increase by step to the maximum the chamber can reach. And the heat flux value at saturation is extrapolated by exponential regression. The same procedure is applied with garments. For each step, the mean temperature of the surface of each segment of the manikin is regulated at 33°C. Temperatures and water flows are measured for each step over 7 minutes. Local and total heat fluxes are then calculated for each step. And the heat fluxes for saturation are calculated by extrapolation. The equipments are classified depending on their heat fluxes (global and local values).

Conclusions

In order to evaluate textiles and clothings protective capacities standards, the steam laboratory develops specifc tools and adapts expert apraisals processes. The laboratory is also destinated to study the physiopathology of steam injuries and to practise the crew members likely to be exposed to steam stresses.

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Measurement of Glove Permeation by Using an Instrumented Thermal and Sweating Hand

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Summary

The hand protection of soldiers working in extreme climatic or tropical conditions requires specific protective gloves that allow them to perform their mission. Protective gloves, that reduce sweat evaporation decrease their manual capabilities and their ability to manipulate small pieces. The instrumented thermal and sweating hand, is fitted to simulate human sweating characteristics. In addition to the measurement of glove permeation, it also allows to quantify precisely the maximal sweat transfert through technical gloves. This measurement allows to underline its contribution to the global insulation of the worn protective equipment. The test protocol allows to determine quickly the efficiency of sweat permeation through protective gloves. This sort of evaluation is an complementary and obligatory preliminary step before dexterity test on human subjects in laboratory.

1. Introduction

The hand protection of soldiers working in extreme climatic or tropical conditions requires specific protective gloves that allow them to perform their mission. Protective gloves that reduce sweat evaporation increase skin temperature and decrease their manual capabilities and their ability to manipulate small pieces.

2. Method

The instrumented thermal and sweating hand is fitted to simulate human sweating characteristics. In addition to the measurement of glove permeation it also allows to quantify precisely the maximal sweat permeability through technical gloves. This measurement allows to underline its contribution to the global insulation of the worn protective equipment.

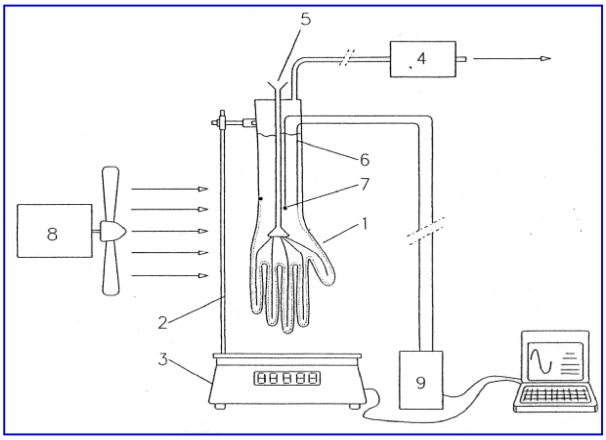

Figure 1 : Principle of the measurement

Figure 2 : The measurement system

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

A porous porcelain hand containing clean water is heated and regulated by a computer. The part of water evaporated through the artificial hand is continuously weighted and monitored by the computer.

Technical parameters		Measurements
Ambient temperature	24±0.5 °C,	Heating power (Watts)
Humidity	40±5%	Heat flow (W/m²)
Simulated core temperature	37±0.5°C	Total evaporated water (g)
Wind speed	< 0.30 m/s	Sweat rate (g/h)
		Skin temperature (°C)

3. Results

The sweat evaporation flow of different concepts of gloves were tested with the thermal and sweating instrumented hand in comparison with the naked hand : butyl, butyl with cotton under-gloves and four models of new generation permeable gloves.

	bare hand	Butyl	Butyl Ug cotton	NBC type G	NBC Type W	NBC Type v 3	NBC Type v 4
Skin temperature	33.1±0.1	34.4±0.2	34.7±0.5	30.7±0.2	32.7±0.7	32.5±0.1	34.3±0.1
Evaporated Water (g/h)	46.8±0.6	1.1±0.4	1.0±0.4	18.2±1.3	16.0±1.1	16.7±1.3	15.4±0.9

Table 1 : Skin temperature and evaporated simulate sweat through gloves.

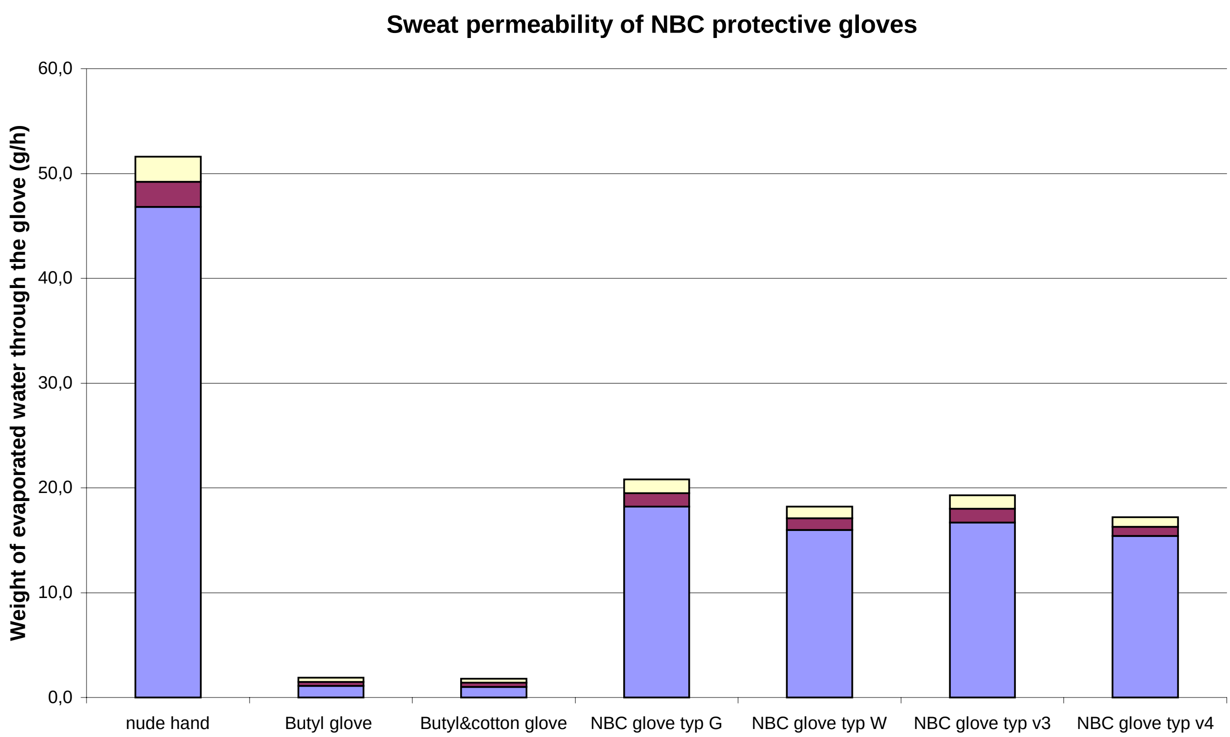

Figure 3 : Sweat permeability through protective gloves

4. Conclusions

The test protocol allows to determine quickly the efficiency of sweat permeation through protective gloves. The sweat evaporation is strongly limited by the butyl glove but in comparaison with the naked hand, all NBC permeable protective gloves allow the half natural flow rate.

This type of evaluation is a complementary and obligatory preliminary step before dexterity tests on humans in laboratory.

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Assessment of Clothing Permeation Using an Instrumented Heated and Sweating Manikin

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Summary

The body protection of soldiers working in extreme climatic or tropical conditions requires a particular protective clothing that allows them to perform their mission. Protective suits, increasing insulation and reducing sweat evaporation, decrease their physiological capabilities and their ability to work in hot and wet environment. The instrumented thermal and sweating manikin is fitted to simulate human sweating characteristics. In addition to the measurement of vapour permeation, it also allows to quantify precisely the maximal sweat transfert of protective clothing. This measurement allows to underline the part of global insulation due to the wet exchange of the worn protective equipment. Different concepts of clothing are tested with the thermal and sweating instrumented manikin, in comparison with the sweat flow of the naked manikin skin : butyl, battle dress, NBC protective suit (charcoal foam and fabric), and different models of new generation permeable clothing.
The test protocol allows to determine quickly the efficiency of sweat permeation through protective equipment. The sweat evaporation is strongly limited by the butyl suit, but in comparaison with naked manikin, NBC permeable protective clothing allow significant flow rate. This evaluation is a complementary and obligatory preliminary step before physiological test on human in laboratory and on the field.

1. Introduction

The body protection of soldiers working in extreme climatic or tropical conditions requires a particular protective clothing that allows them to perform their mission. Protective suits decrease their physiological capabilities and their ability to work in hot and wet environment, according to the increasing of insulation and the reducing of sweat evaporation.

2. Method

Within the frame of a CEB contract, an instrumented heated and sweating manikin has been designed and manufactured by the French company FENZY to simulate human sweating characteristics. In addition in addition to the measurement of the vapour permeation, it also permits to quantify the maximal sweat transfer through protective clothing. This measurement allows to point out the wet exchange to the global insulation of the worn protective equipment.

A thermal instrumented manikin, with humid skin which evaporates clean water, is heated and regulated by desktop computer. The part of water evaporated through the artificial body is continuously weighted and monitored by the computer. Internal and skin temperatures are continuously measured (16 thermal sensors).

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Figure 1: The instrumented thermal and sweating manikin.

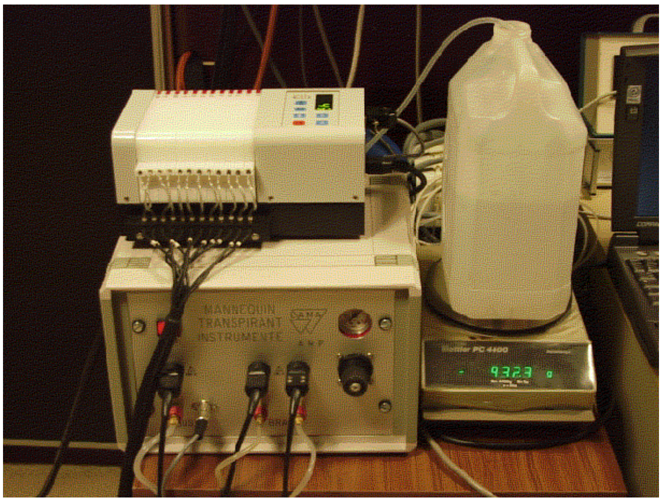

Figure 2 : The command system

Technical parameters

- Climatic Chamber

Ambient temperature 24 ± 0.5 °C
Humidity 60 ± 5%
Wind speed 0.30 m/s-2.0 m/s

- Manikin

max heating power 400 W/m²
Simulated skin temperature 34 ± 0.5°C

Measurements

Heating power (Watts)
Heat flow (W/m²)
Total evaporated water (g)
Sweat rate (g/h)
Internal and skin temperature (°C)
dry and wet Insulation (Clo)

3. Results

Different concepts of clothing are tested with the heated and sweating instrumented manikin, in comparison with the sweat flow naked manikin skin : microporous and impermeable (PVE) protective clothing , battle dress, NBC protective suit (charcoal foam and fabric), and other models of new generation permeable clothing.

situation	Nude dry manikin	Nude wet manikin	battle dress	NBC type MP	NBC type S	NBC type L	PVE suit
Insulation (clo)	1.48+0.02	0.40+0.01	0.53+0.03	0.66+0.04	0.60+0.07	0.54+0.02	1.05+0.08
Heating power (W/m²)	57+6	216+11	90+6	80+2	83+6	89+2	58+4
Evaporated Water (g/h)	0.0	1180± 15	162± 11	159± 1.5	375± 111	425± 17	99± 5

Table 1 : Insulation and simulate evaporated sweat through the clothing. (First results)

4. Conclusion

This test protocol allows determining quickly the level of sweat permeation through protective equipment. The sweat evaporation rate is strongly limited by the PVE protective suit, but in comparison with the naked manikin, NBC permeable protective clothing allow the highest flow rate and impermeable suit provides condensation on internal layer. These first results need to be continued.

This type of evaluation is a complementary and obligatory preliminary step before physiological test on human in laboratory and on the field.

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Light NBC Protective Combat Suits and Body Hydration During Physical Activities Under Tropical Climate

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Summary

When wearing NBC protective suits in full protection mode, rehydration is fundamental to avoid large dehydration. However the gas mask constitutes a potential constraint for drink ingestion. The aim of this study was to evaluate in a hot country the effect of wearing different light NBC protective combat suits on body hydration during various physical activities.

In tropical country, six soldiers have performed moderate and sustained physical activities with different combat suits : standard battle dress and 4 light NBC protective combat suits in full protection mode. Moderate exercise consisted to walk at 4 km/h during 30 min under the sun. Then, subjects sat down under the shade for 30 min (recovery) during which spontaneous rehydration through the gas mask was possible. Sustained exercise consisted to perform the training run of the soldier. Rehydration was provided using imposed rehydration just after the run and rehydration *ad libitum* during the recovery.

During moderate exercise, the sweat rates were higher with TcNBCA and TcNBCB than with the other suits. After exercise, the PV decrease was higher with NBC suits than with standard battle dress. During recovery, the amounts of ingested water were lowered with NBC protective suits (through the gas mask) and were insufficient to correct the water losses and PV reductions. During sustained exercise, the sweat rates were twofold higher with NBC suits than with standard battle dress ($P<0.05$). The large PV decrease (about -6%) just after the run, whatever the suits, could rather be due to the intensity of exercise than to the water losses. Maximal amounts of water ingested through the gas mask after the run were small and insufficient to compensate efficaciously the fluid losses.

Our results have shown the importance of the fluid losses when wearing light NBC suits in full protection mode during various exercises in hot country. Rehydration through the gas mask was uneasy and did not allow to compensate effectively the water losses.

Introduction

The improvements of nuclear, biological and chemical (NBC) protection have allowed to develop light NBC protective suits which permit the combat in similar conditions than using standard battle dresses. However, in full protection mode (gas mask, gloves, hood in place) the body heat elimination is reduced and resulting dehydration can be very large. In these conditions, rehydration is fundamental but the gas mask constitutes a potential constraint for drink ingestion. The purpose of this investigation was to evaluate in a hot country the effect of wearing different light NBC protective combat suits on body hydration during various physical activities.

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

Methods

Six soldiers from an operational group have participed to the experimental protocol in tropical country (Tair : 30-34°C, relative humidity : 55-75%). Each subject has performed 5 moderate and 5 sustained physical activities using different combat suits : standard battle dress (as reference) and 4 light NBC protective combat suits in full protection mode (TcNBC-O : charcoal impregnated compressed foam, Tc NBC-A : new charcoal impregnated compressed foam, Tc NBC-B : spherical particles, Tc NBC-C : activated charcoal cloth).

Moderate exercise consisted to walk at 4 km/h during 30 minutes under the sun. Before and after, subjects sat down under the shade of an open tent for 10 and 30 minutes (recovery) respectively. During the recovery spontaneous rehydration (mineral water) through the gas mask was then possible.

Sustained exercise consisted to perform the training run of the soldier (500 m and 20 obstacles). A recovery period of about 85 min was observed between each run in comfortable conditions (under the shade and wearing light clothing). Rehydration was provided using 2 modalities : imposed rehydration (maximal ingestion of water during 30 s through the gas mask) just after the run and rehydration *ad libitum* during the recovery.

Measurements. Before and after each test, subjects were weighed nude and urine was collected (volume, osmolality and density). Hematocrit, to estimate plasma volume (PV) variation, was obtained before and after each exercise, and at the end of the recovery. Heart rate (HR), and rectal and skin temperatures (Tre and Tsk respectively) were continuously monitored.

Results

During the tests comprising moderate exercise the sweat rates were higher with Tc NBC-A and Tc NBC-B than with other suits (P <0.05). The time courses of Tre and Tsk confirmed the best results obtained with Tc NBCO and Tc NBC-C compared to the other NBC protective suits. After exercise, the PV decrease was higher with NBC suits than with standard battle dress (P <0.05).

	SBD	**Tc NBC-O**	**Tc NBC-A**	**Tc NBC-B**	**Tc NBC-C**
sweat rates (ml)	**768 ± 139**	**815 ± 55**	**991 ± 32**	**895 ± 49**	**716 ± 65**
ingested water (ml)	**338 ± 67**	*** 248 ± 73**	**296 ± 84**	**286 ± 80**	**197 ± 68**
total dehydration (ml)	**429 ± 96**	**567 ± 81**	**646 ± 85**	**611 ± 98**	**519 ± 94**

Table 1 : Sweat rates, amounts of ingested water and total dehydration in six subjects after moderate exercise and recovery when wearing different combat suits : standard battle dress (SBD) and 4 light NBC protective suits.
P < 0.05 compared to SBD values ; **+** P < 0.05 compared to Tc NBC-O values;
P < 0.05 compared to Tc NBC-C values.

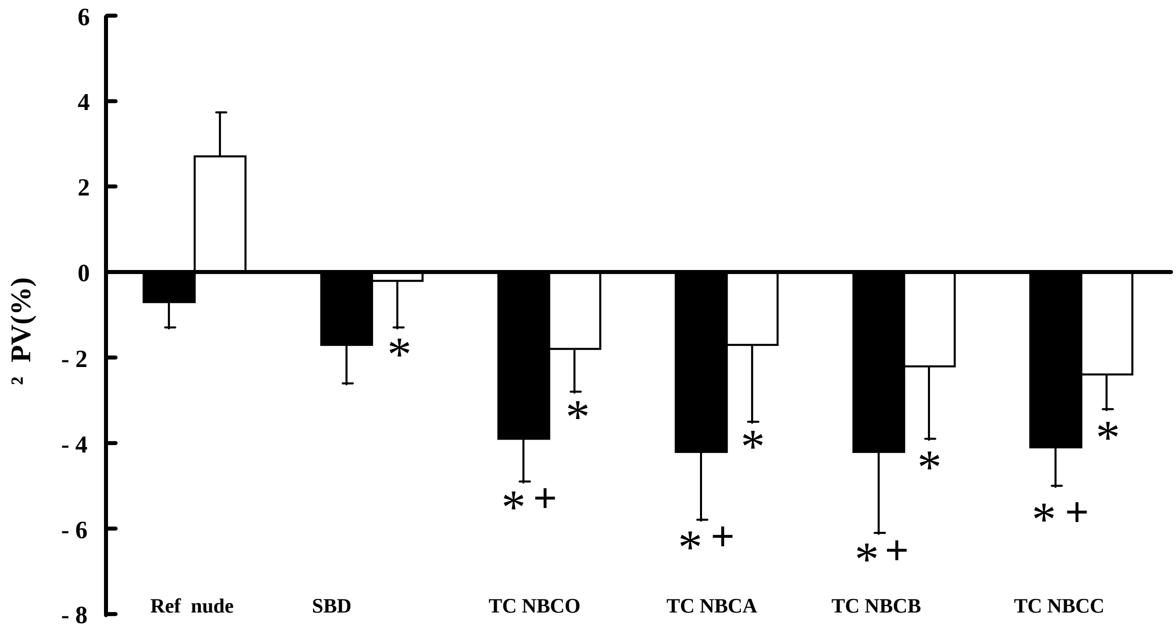

Figure 1 : Plasma volume variation ΔPV (means ± SEM) in six subjects after moderate exercise (.) and recovery (.) during reference test (Ref nude) and when wearing different combat suits : standard battle dress (SBD) and 4 light NBC protective combat suits (TC NBC-O, TC NBC-A, TC NBC-B, TC NBC-C).

***** *P*<0.05 compared to Ref nude values ; **+** *P*<0.05 compared to SBD values.

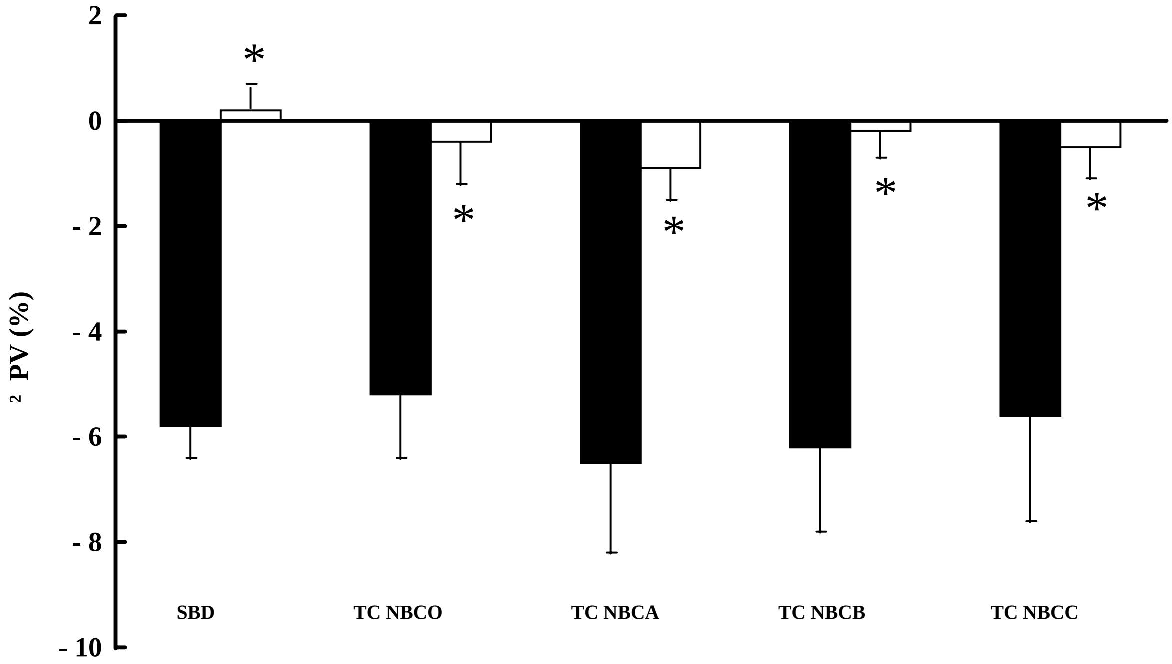

Figure 2 : Plasma volume variation ΔPV (means ± SEM) in six subjects after sustained exercise (.) and recovery (.) with different combat suits : standard battle dress (SBD) and 4 light NBC protective combat suits (TC NBC-O, TC NBC-A, TC NBC-B, TC NBC-C).

***** *P*<0.05 compared to exercise values.

During recovery, the amounts of ingested water (through the gas mask) were lower using NBC protective suits (*P* <0.05) and were insufficient to correct the water losses and plasma volume reductions. The urinary volume was also reduced while osmolality and density increased (*P* <0.05).

The sustained exercise was performed with similar duration whatever the suits (5 min 20 s to 5 min 50 s). However, the sweat rates were twofold higher with NBC suits than with standard battle dress (*P* <0.05). The large PV decrease (about -6%) just after the run, whatever the suits, could be rather due to the intensity of exercise than the water losses. Maximal amounts of water ingested through the gas mask after the run were small (about 60 to 90 ml during 30 s) and insufficient to compensate efficaciously the fluid losses.

Conclusion

Our results have shown the importance of the fluid losses when wearing light NBC suits in full protection mode during various exercises in hot country. Rehydration through the gas mask was uneasy and did not allow to compensate effectively the water losses.

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84 Hours of Exertional Fatigue, Negative Energy Balance, and Sleep Deprivation Impairs Shivering During Cold Air Exposure in Men

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Summary

Long-term (61-d) military operations that induce exertional fatigue, caloric deficiency, and sleep deprivation impair thermoregulatory responses to cold. However, there is no information regarding thermoregulation following short-term (3.5-d) sustained military operations (SUSOPS). This study examined thermoregulatory control during cold exposure following this multi-factorial stress. Thermoregulation of six men (22.8 ± 1.4 yrs) was assessed during a standardized cold air test (SCT) both before (CONTROL) and following an 84-h SUSOPS (sleep = 2-h·d^{-1}, energy intake = ~1800 kcal·d^{-1}, energy expenditure = ~5000 kcal·d^{-1}). SCT consisted of a ramp from 25°C to 10°C during the initial 30-min, with the ambient temperature then remaining at 10°C for an additional 150-min. SUSOPS decreased ($P < 0.05$) body weight, % body fat, and fat free mass by 3.9 kg, 1.6 %, and 1.8 kg, respectively. Metabolic heat production was lower ($P < 0.05$) during CAT following SUSOPS. Examination of the mean body temperature-metabolic heat production relationship indicated that the threshold for shivering was lower ($P < 0.05$) following SUSOPS (34.61°C) than CONTROL (35.73°C). There were no differences between trials in either peripheral heat flow (W·m^{-2}) or mean weighted skin temperature (°C). Partitional calorimetry revealed that body heat content tended to decrease ($P = 0.09$) more during the CAT following SUSOPS (-1298 kJ) vs. CONTROL (-1164 kJ). These results indicate that 84-h of SUSOPS impairs the shivering response to cold exposure but does not increase the risk of hypothermia after 3-h of cold air exposure, but may potentially increase risk during longer exposures.

Introduction

Future military conflicts are expected to involve small rapidly mobile units who will work at a high intensity for sustained periods of time with sufficient, but limited, supplies to support work for several days. It is expected that the soldiers will work long hours with minimal sleep and will likely eat insufficient calories to balance caloric expenditure. Under such conditions, physiological alterations could occur which would compromise soldier performance and thermoregulation (1, 2, 14).

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The individual effects of SUSOPS stressors including exertional fatigue, sleep deprivation, and energy deficits on thermoregulation in the cold have been studied, although not thoroughly. However, there are no studies examining how a short term (2-4 days) multifactorial SUSOPS affects thermoregulation in a cold environment. Only one study has reported the interaction of multiple factors on thermoregulation in the cold, but responses were examined after a long-term military course. In that study, our laboratory (14) studied 15 US Army Rangers following completion of their 61-day training interval. We found that immediately following Ranger School, shivering thermogenesis and peripheral heat retention were blunted, thus body temperature could not be maintained. Although this study gives insight into potential mechanisms that may be compromised during SUSOPS, the length of Ranger training leads to physiological changes (7.4 kg weight loss, substantial insulation loss) not likely to occur during a 72-80 hour sustained operation.

Studies examining sleep deprivation have generally observed no effect on acute cold responses, but the methodologies and study protocols preclude any definitive conclusions. For example, Fiorica et al. (4) observed no effect following 82-h of sleep deprivation, but in their control group, rectal temperature progressively increased over 4 days, despite testing at the same time of day and accounted for the differences in resting T_{re} before cold exposure. Kolka et al. (7) measured thermoregulatory responses during exercise in cold air which resulted in greater heat storage and elevated core temperatures. Thus, that study did not examine physiological adjustments needed to prevent a fall in core temperature. Finally, Savourey and Bittel (13) utilized only a 27-h period of sleep deprivation, which was likely inadequate to cause an effect. In summary, the studies to date suggest that sleep deprivation does not impair thermoregulatory responses to acute cold exposure. The studies however do suggest that T_{re} is regulated at a lower set point after a prolonged period (> 50-h) of sleep deprivation. Likewise, following a sustained operations field study, Bahr et al. (11) reported that core temperature was depressed 0.55°C. This finding is important as a lower starting core temperature may increase the risk of hypothermia (3).

MacDonald and associates have studied the effect of short term fasting (36-48 hours) on thermoregulatory responses during cold exposure, both at rest and during exercise. Generally, they found that T_{re} is not maintained as well after fasting in men (8) and women (9), either at rest or during exercise. At rest, the mechanism appears to be greater peripheral heat loss as blood flow is significantly greater following fasting both in thermoneutral and cool environments. In the study with women, metabolic heat production was also blunted during cooling. While this response was not observed in the men, the men's data suggest that heat production, as a function of core temperature, may also be attenuated.

Our laboratory has recently (1, 2) been examining the concept of "thermoregulatory fatigue", defined as a blunting of the shivering and/or vasoconstrictor response to cold exposure, relative to control conditions. For example, Castellani et al. (2) showed that one hour of leg exercise before cold exposure causes core temperature to fall to a greater degree than under control conditions. The mechanism is greater peripheral heat loss as shivering thermogenesis was not affected. Castellani et al. (1) also have shown that 3 days of exhaustive exercise followed by a 6-h cold exposure causes T_{re} to fall significantly. Again, the mechanism appears to be thermoregulatory fatigue of the vasoconstrictor response as mean skin temperatures were higher and metabolic heat production was unaffected, compared to control trials. This latter study only examined exertional fatigue as a potential stressor since the subjects slept 6-7 hours per night and consumed ~2500 kilocalories per day.

The purpose of this study was to examine thermoregulatory effector responses (shivering, vasoconstriction) following 84 hours of sustained operations. It was hypothesized that thermoregulatory fatigue of both shivering and vasoconstriction would occur following 84 hours of sustained operations.

Methods

Subjects. Six healthy soldiers volunteered to participate in this study as test subjects. Physical characteristics were age, 22.8 ± 1.4 (SE) yr; height, 186 ± 8 cm; mass, 84.3 ± 3.5 kg; and percent body fat, 18.1 ± 2.2 %.

Preliminary Testing. Height, body mass, and % body fat (dual energy x-ray absorbitometry; Model DPX-L, Lunar Corp., Madison, WI) were obtained before the experiment. Mass and % fat were also obtained following the 84-h sustained operation.

Experimental Design. Subjects completed two experimental cold exposure trials, between 1300-1630 hours, on separate days, spaced by one week. Each trial consisted of a standardized cold air test (SCT) preceded by one of two manipulations: A) Control or B) following SUSOPS. During the Control week, subjects were not sleep deprived or in a state of negative energy balance. However, they did perform or were subjected to a variety of physical and cognitive tests before undergoing the SCT. During the SUSOPS week, subjects performed the same physical and cognitive tests before the SCT, but overlaid on them was a limited amount of sleep and food (see below). Subjects consumed the cracker and spread from an Army Meal-Ready-to-Eat (MRE) ~105-min prior to the SCT. The subjects were dressed in only shorts, socks and woolen glove liners for the SCT. Baseline values for temperature, metabolic heat production, plasma norepinephrine, and thermal sensation were collected during a 20-minute period with conditions maintained at 25°C and 50% RH. Following this, T_{amb} was reduced by 0.5°C·min^{-1} over a thirty-minute period, after which T_{amb} was maintained constant at 10°C and 50% RH for an additional 150 minutes. Oxygen uptake, carbon dioxide output, and minute ventilation were measured by open-circuit spirometry at min 30, 60, 90, 120 and 150. T_{re} and mean skin temperature (T_{sk}) were obtained every minute. While exposed to the cold, the subjects were not allowed to employ behavioral thermoregulation (no unnecessary physical activity or "huddling").

Sustained Operations. The experiment consisted of 84 h (from 0600-h on Day 1 to 1800-h, Day 4) of sustained physical activity with limited time allotted for sleep and only ~1,800 kcal of food per day. Forty-nine hours of this time period was spent doing military-relevant field exercises. The timetable of experimental tests during the Control and SUSOPS weeks is presented in Figure 1 below.

Sleep was restricted by scheduling only limited blocks of sleep and keeping soldiers busy performing mental and physical tasks for the majority of each 24 h day. Two hours per day were scheduled for sleep and sleep patterns were monitored via actigraph activity monitors.

Subjects consumed one US Army Meal-Ready-to-Eat per day during the SUSOPS week, supplemented with a bagel, juice, and a piece of fruit on the morning of Days 1, 3, and 4 and a candy bar on Day 2. Estimated caloric intake was ~1800 kilocalories per day with an estimated energy expenditure of 5000 kilocalories per day.

Physical performance tests before each SCT were the same during the Control and SUSOPS weeks. In brief, these tests consisted of an obstacle course (2 runs, ~35-sec duration), two power tests (bench throw, squat jump; ~ 30-sec duration), and a repetitive box lift for 10-min. These performance tasks occurred between 0930-1115 hours with rest scheduled between tasks.

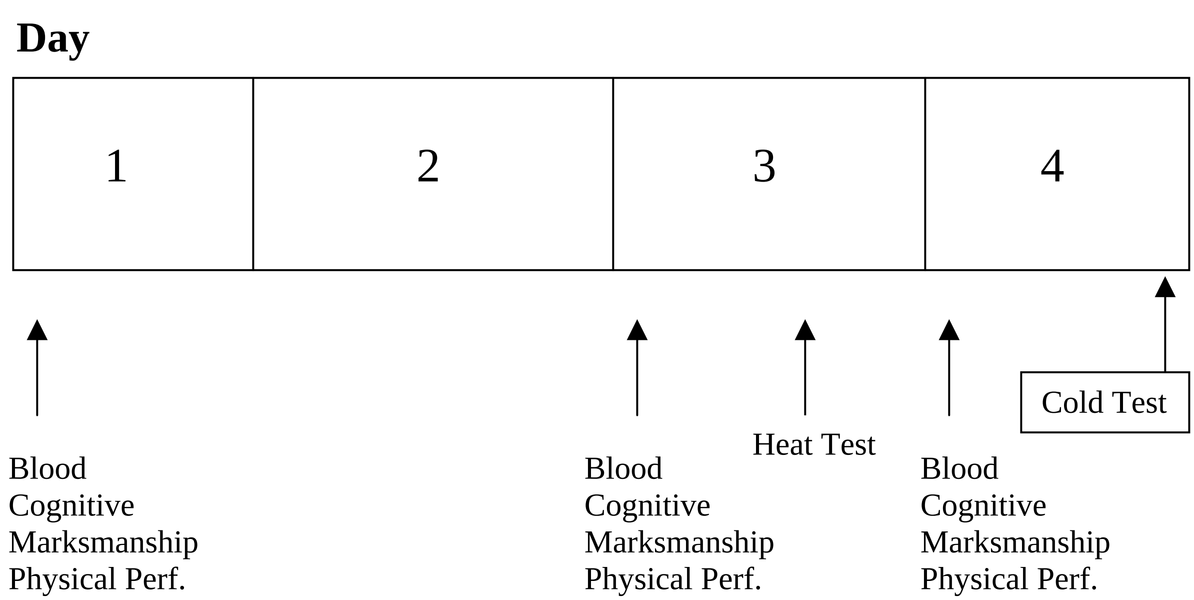

Figure 1. Experimental tests performed during Control and SUSOPS weeks.

Measurements and calculations. Rectal temperature (T_{re}; n = 5) was measured using a thermistor inserted 10 cm past the anal sphincter. Esophageal temperature (T_{es}; n =1) was measured using a thermistor inserted into the esophagus to a length of ¼ body height. Skin temperature (T_{sk}) was measured using thermistor disk sensors (Concept Engineering, Old Saybrook, CT) attached on the skin surface (right side of body) at five sites (calf, medial thigh, tricep, forearm (ventral), and subscapular). Mean weighted skin temperature (T_{sk}) was calculated as: $T_{sk} = 0.28T_{subscapular} + 0.14T_{forearm} + 0.08T_{triceps} + 0.22T_{calf} + 0.28T_{thigh}$. Mean body temperature (T_b) during cold exposure was calculated as follows: $T_b = 0.67 \bullet T_{re(es)} + 0.33 \bullet T_{sk}$. Percent oxygen (Model S-3A, Applied Electrochemistry) carbon dioxide (model LB-2, Beckman) and volume (Tissot spirometer, Collins) were measured from a 90-sec collection of the subjects' air expired into a 150L Douglas Bag. Metabolic heat production ($W \cdot m^{-2}$) was estimated from VO_2 and respiratory exchange ratio (R) using the following equation: $M = (0.23[R] + 0.77) \bullet (5.873)(VO_2) \bullet (60/A_D)$ where A_D is body surface area (m^2). Body heat storage (S, $W \cdot m^{-2}$) was calculated as follows (7): $\pm S = M - W - L - E - K - (R+C)$, where M is the metabolic rate, W is work rate (0 in this experiment), L is the respiratory heat losses by convection and evaporation ($0.08 \bullet M$), E is evaporative heat loss (presumed to be negligible in this experiment and set at 0), K represents conductive heat loss (0 in this experiment) and R+C ($0.83 \bullet [T_{re}-T_{sk}]$) represents dry heat loss.

Whole blood samples were drawn before cold exposure (min 0) and at minutes 30 and 175 of cold air exposure from an indwelling venous catheter (18 gauge) placed in a superficial forearm vein. Aliquots were centrifuged at 4°C to separate the plasma. Plasma samples were frozen at -40°C before analysis. Plasma norepinephrine (NE) concentration was determined from mass spectroscopy-gas chromatography.

Statistical Analyses. Data were analyzed using a two-factor (experimental trial X time) repeated measures ANOVA. When significant F ratios were calculated, paired comparisons were made post-hoc using a Newman-Keuls test. The slope and intercept of each individual's T_b vs. ΔM relationship, as well as body composition variables were analyzed using repeated t-tests. Unless otherwise specified, the level of significance for differences reported is $P < 0.05$. Values are mean ± SE.

Results

Body Composition. Body composition changes are presented in Figure 2. Body mass, % body fat, and fat free mass significantly declined ($P < 0.05$) after SUSOPS.

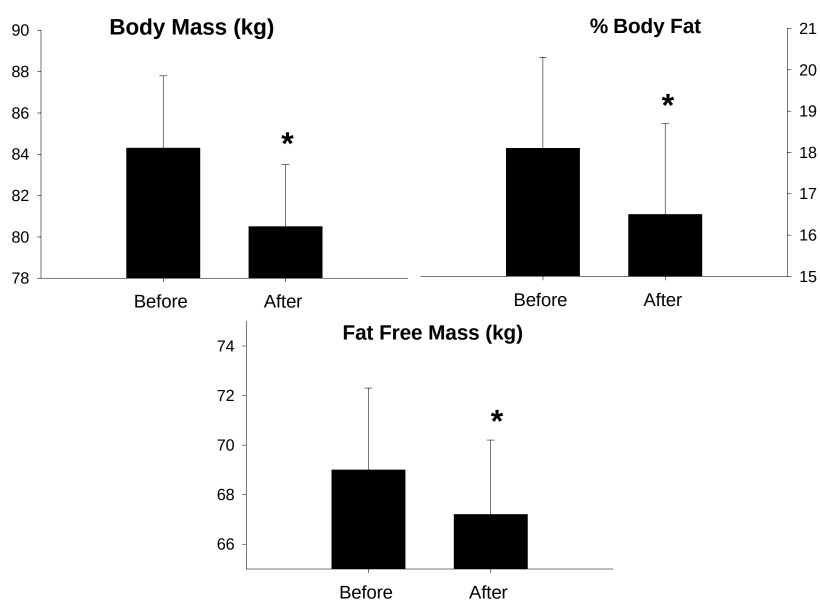

Figure 2. Body composition changes before and after SUSOPS.

Thermoregulatory Responses. Metabolic heat production was significantly lower ($P < 0.05$) at min 30, 60, and 90 during SUSOPS compared to the Control trial (Figure 3).

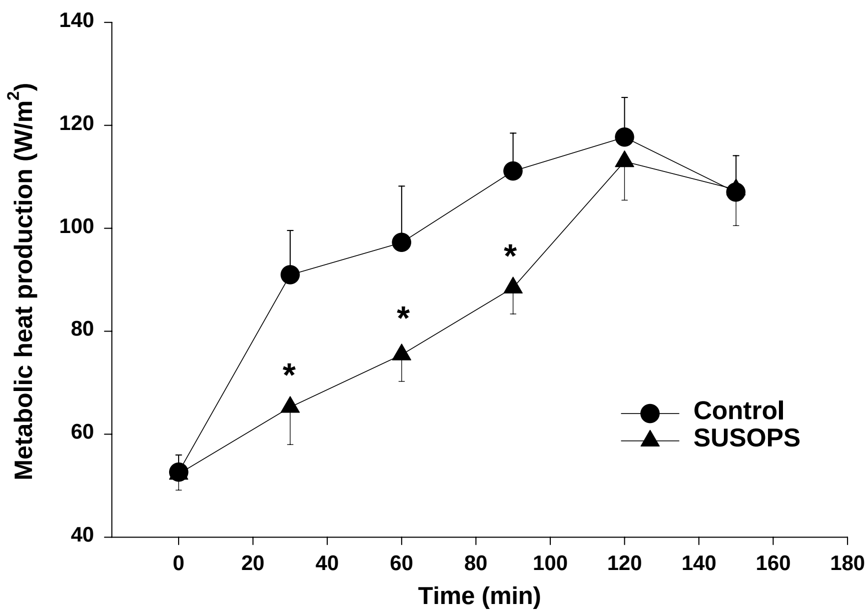

Figure 3. Metabolic heat production vs. time during Control and SUSOPS trials.

The slopes of the T_b-ΔM relationship (Figure 4) between the Control (-28.3 ± 4.9 W·m^{-2}·°C^{-1}) and SUSOPS (-58.0 ± 14.1 W·m^{-2}·°C^{-1}) trials approached significance ($P = 0.06$). However, there was a significant ($P < 0.05$) difference in the threshold for the onset of shivering between Control (35.73 ± 0.10°C) and SUSOPS (34.61 ± 0.19°C).

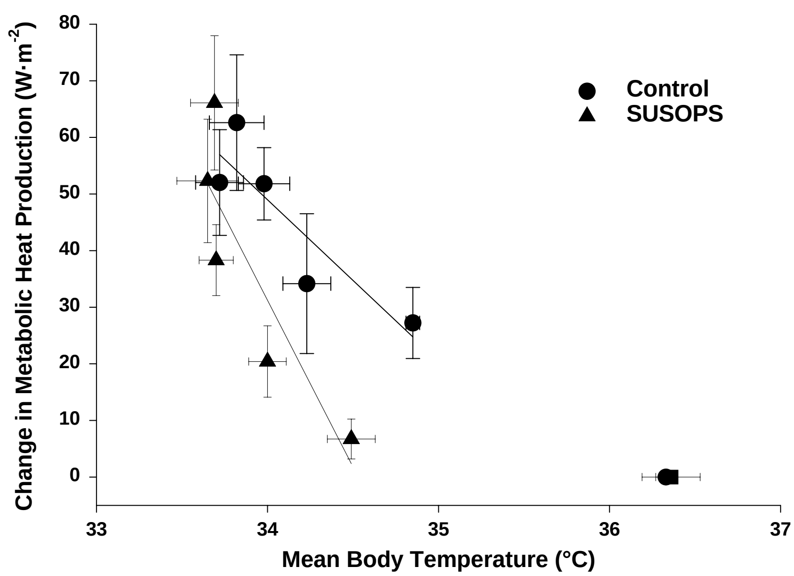

Figure 4. T_b-ΔM relationship during Control and SUSOPS trials (n = 4).

Mean skin temperatures were not significantly different between the two trials (at min 180, 26.75 ± 0.31°C and 26.44 ± 0.39°C for Control and SUSOPS, respectively). There also were no differences (P = 0.09) in the change in body heat content (Figure 5) and change in rectal temperature (Figure 6) between Control and SUSOPS trials.

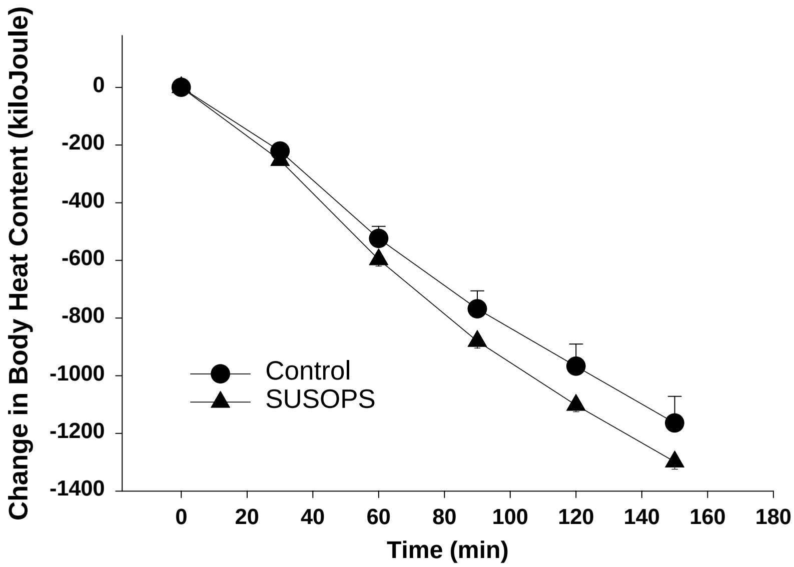

Figure 5. Change in body heat content (kJ) vs. time between Control and SUSOPS trials.

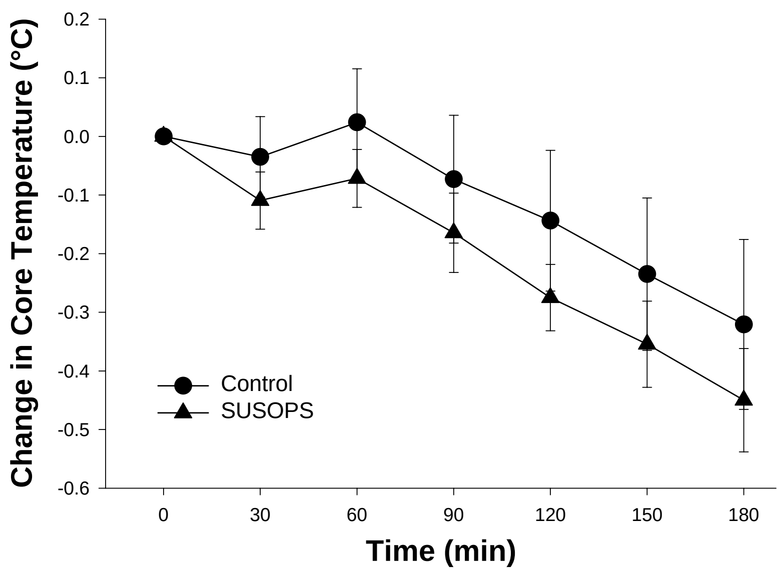

Figure 6. Change in core temperature (°C) vs. time between Control and SUSOPS trials. Initial core temperatures were 37.24 ± 0.11 and 37.26 ± 0.11, for Control and SUSOPS, respectively.

Plasma glucose and catecholamines. Plasma concentrations for glucose and norepinephrine are presented below in Tables 1 and 2. There were no significant differences within or between trials for glucose. Plasma norepinephrine was significantly higher (main effect) during SUSOPS compared to Control.

Table 1. Plasma glucose concentrations ($mmol \cdot L^{-1}$)

Time	Control	SUSOPS
Pre	5.00 ± 0.17 (n = 6)	5.00 ± 0.62 (n = 5)
30-min	4.47 ± 0.37 (n = 5)	4.92 ± 0.18 (n = 4)
175-min	4.57 ± 0.18 (n = 4)	4.67 ± 0.12 (n = 4)

Table 2. Plasma norepinephrine concentrations ($pg \cdot ml^{-1}$)

Time	Control	SUSOPS‡
Pre	820.5 ± 57.8 (n = 6)	1144.6 ± 179.8 (n = 6)
30-min	1868.5 ± 274.1* (n = 4)	3392.7 ± 808.4* (n = 4)
175-min	3275.0 ± 521.8* (n = 4)	4953.5 ± 344.8* (n = 4)

*, denotes significant within trial difference from Pre; ‡, significant main effect for trial, SUSOPS > Control

Discussion

Military sustained operations (SUSOPS) present a unique physiological challenge to the warfighter. Multiple stresses are imposed on the individual including sleep deprivation, negative energy balance, and heavy physical work. All three of these stressors may, independently, affect thermoregulation in the cold. The combination of these stressors has been shown, during long-term training (14) to impair both the shivering and vasoconstrictor response to cold exposure. However, this is the first study to examine the effects of a 3-4 day SUSOPS that is more common and operationally realistic, without the comparably large changes in subcutaneous fat and percent body fat observed during 61-d US Army Ranger training (14).

The principal finding in this study was the lower metabolic heat production and the lower mean body temperature for the onset of shivering following an 84-h SUSOPS, compared to rested conditions. Two possible independent mechanisms (or their interactions) for this effect are conceivable: sleep deprivation and negative energy balance. Exertional fatigue is ruled out as we have previously demonstrated this has no effect on shivering thermogenesis during subsequent cold exposure.

The role of sleep deprivation on thermoregulatory responses to cold have typically demonstrated no effect on core temperature changes and this study was no exception. However, several interesting findings from previous studies have been reported and are worth noting. For example, Fiorica et al. (4) observed that resting rectal temperatures were significantly lower following 53 and 82 hours of sleep deprivation in a sleep deprived group compared to a set of control subjects. In addition, Kolka et al. (6) also observed lower resting esophageal temperatures after 50 hours of sleep deprivation. However, we did not observe any changes in core temperature at rest just before cold exposure. Our data agree with those reported by Savourey and Bittel (13), in subjects who were sleep deprived for 27 hours. One difference between our data and Fiorica et al. (4) is that group employed a separate non-sleep deprived control group, who over the course of the 82-h experiment, experienced a significant rise in resting rectal temperature, whereas the sleep deprived group had no change in resting core temperature, thus accounting for the significant difference

between the groups. Kolka et al. (6) measured only esophageal temperatures and this may partially account for the difference as well. One possibility is that the subjects in this SUSOPS study were physically active (physical performance tests) before cold exposure, whereas in the previous studies, the subjects were sedentary. This may have masked the effect of sleep deprivation on resting core temperature. Whether sleep deprivation, independently, is responsible for the delayed onset of shivering is debatable. In contrast to our findings, Savourey and Bittel (13) found that sleep deprivation increased the sensitivity of the shivering response, such that shivering began earlier. However, that study used a subjective measure of shivering to determine onset as opposed to an objective measure such as changes in oxygen uptake. Further evidence for a delayed shivering onset is provided by Young et al. (14). Subjects in that study were sleep-deprived prior to beginning their initial experimental cold exposure. It is difficult to attribute the changes in shivering thermogenesis solely to sleep deprivation in that study and in the present SUSOPS investigation, due to the multi-factorial stressors present. Examining the effects of 2-3 day sleep deprivation on thermoregulatory responses to the cold are warranted to independently evaluate this factor.

Underfeeding and 48-h fasting have also been suggested to impair thermoregulatory responses to cold (8, 9, 14). In one case (14), it was difficult to discern whether underfeeding (relative to caloric intake) per se was responsible for the blunted shivering and vasoconstrictor responses because large changes in body composition (10% fall in % body fat) also occurred. We observed significant falls in indices of body composition as well, but not severe in magnitude (~1.5% fall in % fat) to account for changes in effector responses. In the other case, the subjects consumed no food at all for 2 days. One obvious difference between studies is that the subjects in SUSOPS were not fasting, as they consumed approximately 1800 kilocalories per day. They also consumed a small meal within 2-h of cold exposure, in order to maintain plasma glucose concentrations during the 3-h cold exposure since low glucose values are known to blunt thermoregulatory effector responses (5, 12). Changes in the core temperature-metabolic rate relationship have also been observed after 48-h fasting. Unlike the changes seen in the present study (a decrease in the shivering onset, i.e., a temperature threshold change), MacDonald and colleagues (8) found the gain or sensitivity of the metabolic response to a given fall in core temperature was blunted after 2 days of fasting in men and a blunted metabolic heat response in women (9). One hypothesis for the diminished thermogenic response is an elevated basal norepinephrine concentration. We did find elevated plasma norepinephrine values at baseline following 4 days of SUSOPS. This has also been observed following either 48-h fasting (9) or a combination of sleep loss, underfeeding, and exertional fatigue (14), potentially causing a down-regulation of beta-adrenergic receptors (10).

Interestingly, SUSOPS caused no changes in the vasoconstrictor response to cold exposure, even though previous work from our laboratory (1, 2) suggests that exertional fatigue blunts the skin temperature response during cold exposure and that the vasoconstrictor response to cold is attenuated following 48-h of fasting (8, 9) and 27 hours of sleep deprivation (13). Why there were no changes following SUSOPS is not known.

In conclusion, SUSOPS decreased the mean body temperature threshold for the onset of shivering thermogenesis. However, peripheral heat loss was not affected by 4 days of exertional fatigue, sleep deprivation, and negative energy balance. Core body temperature and body heat content were also not different following SUSOPS. Thus, even though shivering was blunted, core temperature was not compromised by SUSOPS after 3-h of cold exposure, thus there is no greater risk for hypothermia following an 84-h sustained operation.

Disclaimer

The views, opinions and/or findings in this report are those of the authors and should not be construed as official Department of the Army position, policy, or decision unless so designated by other official designation. Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USMRDC Regulation 70-25 on Use of Volunteers in Research.

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Symptoms at Exhaustion from Uncompensable Exercise-Heat Stress

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Summary

Exhaustion occurs over a broad range of core temperatures during uncompensable exercise-heat stress. This study examined the symptoms at heat exhaustion and whether they differed among individuals terminating exercise at low vs. high core temperatures. Forty-seven healthy, heat-acclimated volunteers exercised to exhaustion during uncompensable heat stress on one or more occasions for a total of 133 trials. Mean core temperature (±sd) at exhaustion was 38.7±0.5°C (range 37.4 to 39.8°C) and was generally consistent within an individual. Volunteers stopped primarily due to ataxia/dizziness (42%), followed by physical exhaustion (25%), headache/nausea (17%), dyspnea (12%) and muscle cramps (4%). Volunteers who terminated at lower core temperatures (≤38.4°C) were limited by physical exhaustion at a rate similar to those stopping at higher (≥39.0°C) core temperatures. However, those who stopped at lower core temperatures had a higher incidence of dyspnea and lower incidence of both ataxia/dizziness and headache/nausea when compared to volunteers terminating exercise at higher core temperatures ($\chi^2 = 10.6$; $P<0.05$). Therefore, heat intolerant persons were more likely to develop respiratory distress while heat tolerant persons were able to continue until cardiovascular and illness symptoms limited further effort. These data suggest that different physiological mechanisms contribute to the inter-subject variability in tolerance to uncompensable exercise-heat stress.

Background

Uncompensable heat stress exists when evaporative capacity of the environment is inadequate to remove the heat being produced. Workers wearing protective clothing such as firefighters, toxicological clean-up workers, soldiers on a chemical-biological battlefield, and others performing strenuous exercise in oppressively hot/humid conditions are exposed to uncompensable heat stress. Under such stress, workers frequently develop symptoms of heat exhaustion and cannot continue to work. Our laboratory (3,4,6,8,9) as well as others (1,5) have reported that soldiers become exhausted over a broad range of core temperatures during uncompensable heat stress. In contrast, authors of studies using trained athletes have reported that all their subjects uniformly became exhausted at relatively high core temperatures (2,7). We hypothesized that the different results between studies might be due to different study populations. To identify if the symptoms at exhaustion differed among individuals terminating exercise at low vs. high core temperatures, we examined the symptoms at exhaustion from several studies our laboratory had conducted over the years (3,4,6,8,9).

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

Methods

Subjects. Forty-seven healthy, heat acclimated soldiers (age 23±5 y, body mass 77±11 kg, body surface area 1.94±0.15 m^2, maximal oxygen consumption 54±7 ml $\cdot kg^{-1} \cdot min^{-1}$) participated as study volunteers after signing an approved informed consent document.

Protocol. Volunteers performed treadmill exercise or roadmarching until they could not continue to exercise on one or more occasions. Uncompensable exercise-heat stress was produced by encapsulating the volunteers in chemical protective clothing (38 volunteers) and/or raising the climatic heat stress to levels restricting heat loss (9 volunteers). The protective clothing consisted of trousers, coat, vinyl overboots, butyl rubber gloves, and chemical protective mask (M-17A1) with impermeable hood and Kevlar helmet. The ensemble was worn over T-shirt, shorts, socks and combat boots. Walking speeds were 1.34 to 1.56 m/sec. Rectal and skin temperatures, and heart rate were measured throughout the exercise period. At exhaustion, volunteers self-reported their reason for discontinuing exercise. The reasons for discontinuation were subsequently placed into one of 6 categories: 1) Syncope/ataxia/dizziness, 2) fatigue, 3)Dyspnea, 4) Muscle cramps, 5) headache/nausea.

Data Analysis. Frequency distributions of core temperatures and symptomatology at exhaustion were determined. The data were then subdivided into two groups, those with core temperatures ≤38.4°C or ≥ 39.0°C at exhaustion and chi square analysis was performed to determine if symptoms at exhaustion differed between the two groups. The core temperatures used were picked as they are 0.3°C above and below the mean core temperature at exhaustion, and this difference is the typical between-subjects standard deviation for the core temperature response to exercise. A $p<0.05$ was used to determine statistical significance. Data are presented as mean±sd.

Results

A total of 133 trials ended due to exhaustion from exercise-heat stress that also had available endpoint core temperature and reason for termination. Figure 1 presents the frequency of exhaustion relative to end-point rectal temperature for these trials. Core temperature at exhaustion averaged 38.7±0.5°C with a median temperature of 38.6°C. Exhaustion occurred over a broad range of temperatures (range 37.4°C to 39.8°C).

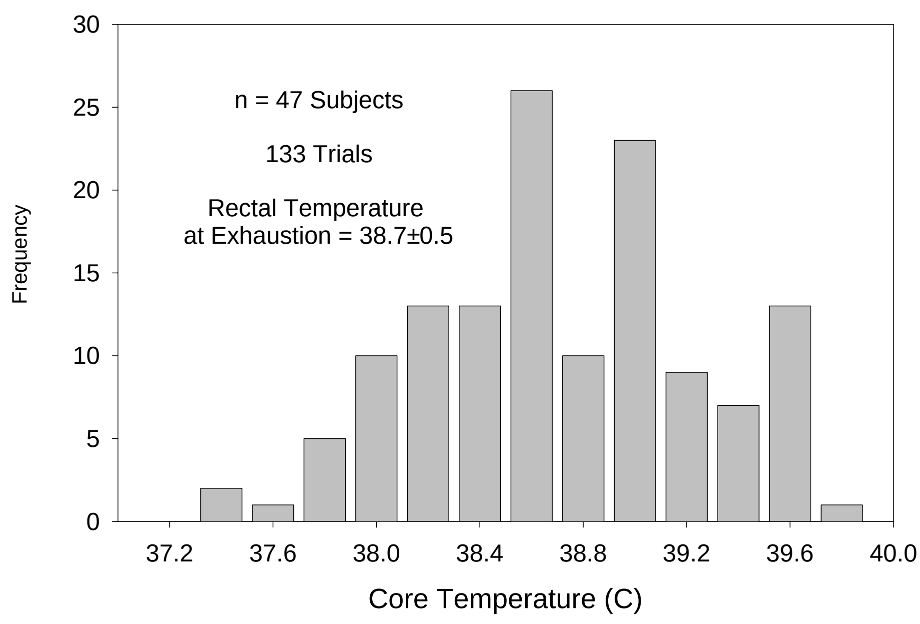

Figure 1. Core temperatures at exhaustion from uncompensable exercise-heat stress.

Figure 2 presents the reason volunteers terminated exercise. Symptoms of syncope/ataxia/dizziness (42% of cases) were the most frequently cited reasons for being unable to continue exercise. Next most frequent were symptoms of fatigue (25%) followed by headache, sickness (17%) , dyspnea (12%) and muscle cramps (4%).

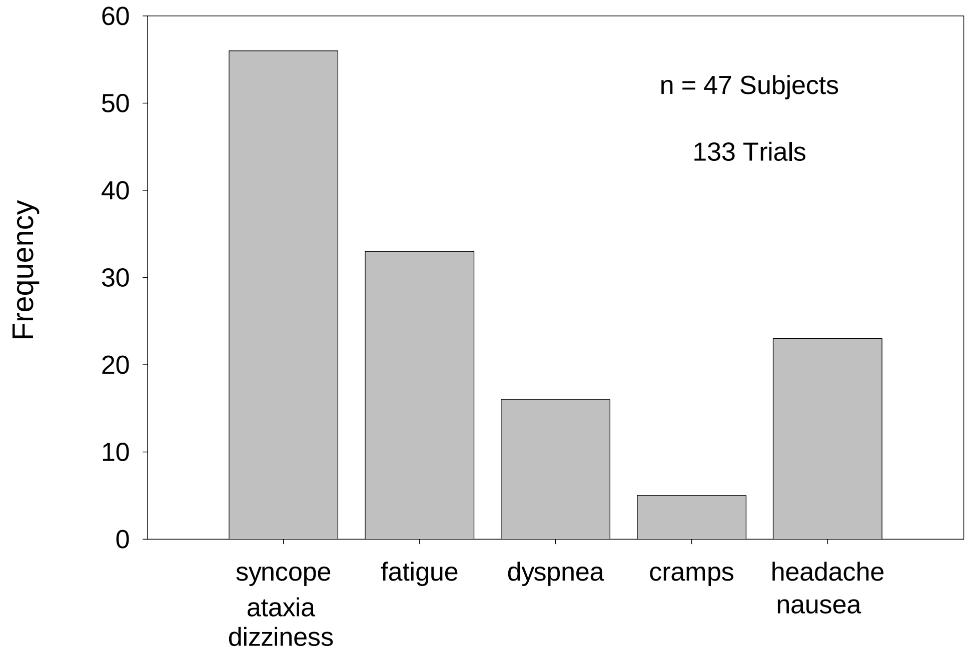

Figure 2. Frequency of symptoms at exhaustion from uncompensable exercise-heat stress.

Separating the cases into two groups based on end-point core temperature revealed a differing set of symptoms between the two groups (Figure 3 and Table 1). Those terminating at core temperatures equal to or below 38.4°C had a higher incidence of dyspnea and lower incidence of syncope/ataxia/dizziness and headache/nausea compared to the group terminating exercise at core temperatures equal to or greater than 39.0°C.

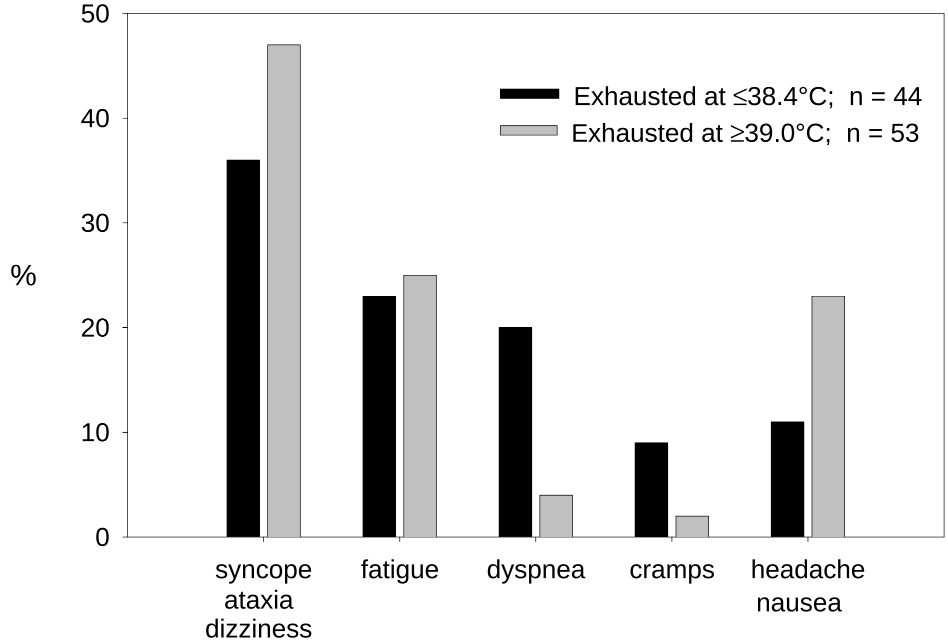

Figure 3. Frequency of symptoms for persons exhausted at low and high core temperatures.

Table 1. Frequency of reason for termination of uncompensable exercise-heat stress for persons with low (≤38.4°C) and high (≤39.0°C) core temperatures at exhaustion.

Temp (°C)	Syncope Ataxia Dizziness	Fatigue	Dyspnea	Cramps	Headache Nausea	Σ
≤38.4°C	16 (36%)	10 (23%)	9 (20%)	4 (9%)	5 (11%)	44
≤39.0°C	25 (47%)	13 (25%)	2 (4%)	1 (2%)	12 (23%)	53
Σ	41 (42%)	23 (24%)	11 (11%)	5 (5%)	17 (18%)	97

Low vs. High Core Temperature at Exhaustion: χ^2 critical= 9.488
χ^2 calculated= 10.62
$p < 0.05$

Discussion

Recent laboratory research has focused on relationships between physiological strain and the incidence rate of exhaustion from heat strain during uncompensable heat stress (1,3-6,8,9) . Studies using physically active but not highly endurance trained volunteers have reported that exhaustion occurred over a broad range of core temperatures. In contrast, studies using endurance trained athletes have reported that core temperatures at exhaustion occurred consistently over 39.5°C (2,7). From the latter studies, has come the idea that there is a critical core temperature and when this temperature is reached, symptoms of fatigue prevent further exercise. We hypothesized that the populations participating in the studies may have contributed to the disparate observations regarding core temperatures at exhaustion. To test this hypothesis, we retrospectively culled the individual reasons for stopping exercise from several studies our Institute had

performed over the years in which volunteers were asked to complete an prescribed exercise duration or exercise as long as possible during uncompensable exercise heat stress. It was anticipated that if the hypothesis were true, the reasons for termination would be different for those individuals who terminated exercise at low core temperatures compared to individuals who did not terminate until core temperature was above 39°C.

Our results support our hypothesis, as the symptomatology at termination of exercise differed between individuals forced to terminate at low core temperatures compared to those who terminated with core temperatures in excess of 39°C degrees. Those who terminated at low core temperatures had a disproportionate number of cases of dyspnea (20% vs 4% of trials) and fewer cases of syncope/ataxia/dizziness and headache/nausea (50% vs 70%) compared to the volunteers who fatigued when core temperatures were in excess of 39°C. Thus, these data suggest that two separate populations of volunteers participated in the studies. Those stopping at low core temperatures stopped more frequently for symptoms related to respiratory distress and muscle cramps, whereas those stopping at higher core temperatures either had limited symptoms of respiratory distress and muscle cramps or were able to tolerate them until the point of cardiovascular instability (syncope/ataxia/dizziness) or heat illness (syncope/ataxia/dizziness and headache/nausea) were attained.

While it is possible that the experimental conditions did impose an added respiratory load and this contributed to the cases of dyspnea, efforts were made to minimize the detrimental effects of wearing protective clothing on the volunteers' motivation to work. All volunteers were required to have prior experience wearing the protective ensemble before being allowed to participate in the studies and in many cases volunteers participated in an acclimation protocol in which they wore the mask for progressively longer periods of time before performing exhaustive exercise. Additionally, in 79 of 124 trials in which protective clothing was worn, the air filter canisters and voice emitter box were removed to minimize respiratory work during exercise. Despite these precautionary steps, dyspnea was the reason cited in 9 of 44 trials (20%) that terminated at core temperatures ≤38.4°C. Trials where the air canister and voice emitter were worn accounted for 3 of 9 cases. No cases of dyspnea occurred when the chemical protective mask was not worn.

Additional support for the contention that population characteristics contributed to the range of heat tolerance exhibited in these studies come from experiments performed either in the laboratory or a field setting. We recently compiled data from both field and laboratory studies performed by our Institute over the past 35 years (8). Volunteers participating in the field studies came from military units training in hot climates whereas for the laboratory studies, the volunteers were primarily soldiers stationed at Natick, MA and heat acclimated for 3-12 days prior to participation. Analysis of core temperatures at exhaustion between the two settings revealed that only 50% of subjects participating in the field studies incurred exhaustion from heat strain at core temperatures below 39.5°C while 50% of the volunteers in the laboratory studies incurred exhaustion below 38.7°C. What specific factors contributed to the differences between groups is not known, but the effect persisted even when low-heat tolerant individuals (persons stopping at core temperatures below 38.3°C) were removed from the dataset.

McLellan and Selkirk (5) directly evaluated the impact of aerobic fitness and regular physical activity on the ability to tolerate uncompensable exercise-heat stress and reach high core temperatures before exhaustion. Subjects in the study were matched for either fitness or fatness and assigned to one of 4 groups: high fit-low fat, high fit-high fat, low fit-low fat or low fit-high fat. The authors found that the individuals who were fit could perform longer than the low fit groups and reached higher core temperatures before becoming exhausted from the heat stress. Thus, these data document that persons who have a high aerobic capacity are more likely to be heat tolerant than those who are less fit and further support the hypothesis that intra-experiment population differences explain at least part of the reason for the broad range of heat tolerance observed in studies of soldier populations compared to endurance trained athletes.

Conclusions

In this study, heat intolerant volunteers were more likely to develop respiratory distress and muscle cramps while heat tolerant persons were able to continue until cardiovascular and illness symptoms limited further effort. The results suggest that different physiological mechanisms contribute to the inter-subject variability in tolerance to uncompensable exercise-heat stress.

Acknowledgements

The views, opinions and/or findings in this report are those of the authors and should not be construed as official Department of the Army position, policy, or decision unless so designated by other official designation. Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USMRDC Regulation 70-25 on Use of Volunteers in Research. Approved for public release; distribution unlimited.

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The Effect of Air Permeability on the Chemical Protective Performance of NBC Suits

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Summary
The heat load imposed by air-permeable NBC-protective suits can be reduced by improving the air permeability of the suit. However increased air permeability will reduce the chemical protective performance. In this study the relation between the chemical protective performance and air permeability of NBC-clothing is evaluated. Mustard vapour challenge tests were performed on a number of NBC protective materials, to evaluate their level of protection. The penetration of mustard vapour was correlated with the dynamic adsorption capacity and the air permeability of the material. The air permeability of the material appears to be a parameter of critical importance. High air permeability of the material is conflicting with a good protective performance. A theoretical model was developed, which describes the chemical protection of air permeable protective clothing material under various conditions. Using this model the effect of airflow through the material on the breakthrough of mustard vapour was calculated and compared with the results of breakthrough experiments. The predictions of the model are in good agreement with the experimental results. The relation between air permeability and protective performance provides an insight in the costs of an adequate protection in terms of physiological load.

Introduction
The NBC-protective clothing currently in use by military forces usually is an air permeable carbon-based garment. This clothing protect the wearer by adsorbing the hazardous chemical vapours onto the carbon. The thermal load of this type of clothing is low in comparison with impermeable clothing, because of the relative good transmission of air and water vapour. The heat stress on the wearer can be nevertheless a problem, especially in hot ambient environments. A reduction of the heat load can be achieved by improving the air permeability of the fabric. However, increased air permeability will reduce the chemical protective performance. In order to achieve a good compromise between comfort and protection it is useful to understand the relationship between the chemical protective performance and the air permeability. This paper presents the results of a theoretical and experimental study about this. The experimental study deals with the evaluation of sixteen NBC-protective fabrics containing various types of carbonaceous layers. A theoretical model which describes the influence of the airflow through the material on the chemical barrier properties of the fabric is presented for one typical carbon type material.

Theoretical
In the theoretical analysis only materials of the carbon bead type have been taken into account. In this type of protective clothing the filter fabric is based on a single layer of small activated carbon spheres, adhered to a carrier fabric. When an activated carbon filter is challenged by a chemical agent vapour flow, the breakthrough curve of the effluent vapour concentration against time is typically sigmoid. Typical of carbon bead type fabrics is an initial step in the breakthrough curve; immediately after exposure a very small breakthrough concentration of vapour occurs, which is roughly constant over a certain period of time. The main aim of this work is to model the initial breakthrough of the vapour.

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Initial breakthrough

Several authors have studied the breakthrough of vapour through carbon filters [1-3]. A commonly used equation, which describes the vapour concentration, C, inside the filter as a function of the axial position, z, in the filter is:

$$\varepsilon \frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - v\frac{\partial C}{\partial z} - k_g(1-\varepsilon)\frac{3}{r}(C - C_s) \qquad (1)$$

C local concentration (kg/m^3)
C_s concentration of vapour, in equilibrium with the adsorbed surface concentration of vapour onto the carbon (kg/m^3)
ε bulk porosity of the carbon particles in the filter (-)
D diffusion coefficient vapour (m^2/s)
v superficial velocity of the air through the clothing (m/s)
k_g mass transfer coefficient vapour between the gas and the carbon (m/s)
t time (s)
z axial position in the filter (m)

In the initial stages of the breakthrough, the surface concentration of vapour on the carbon, C_s, will almost be 0, because no adsorption will have taken place yet. During the initial moments, another assumption can be made: the initial breakthrough will remains constant (experimental results second this assumption). Mathematically this means that:

$$\frac{\partial C}{\partial t} = 0 \qquad (2)$$

Thus:

$$D\frac{\partial^2 C}{\partial z^2} - v\frac{\partial C}{\partial z} - k_g(1-\varepsilon)\frac{3}{r}C = 0 \qquad (3)$$

The boundary conditions of this differential equation are: the concentration, C, is equal to the challenge concentration, C_0, at the inlet of the filter (z=0) and is equal to the breakthrough concentration, C_{ini}, at the end of the filter bed. In the case of carbon bead type fabrics, the filter bed thickness is only one layer of carbon particles. Thus the bed thickness is assumed to be twice the radius of the particle, 2r. Using these boundary conditions, the differential equation can be solved. This gives for the breakthrough concentration:

$$C_{ini} = C_0 \exp\left(\frac{vr}{D}\left(1 - \sqrt{1 + 12(1-\varepsilon)\frac{D}{rv^2}k_g}\right)\right) \qquad (4)$$

The mass transfer coefficient can be calculated with the number of Sherwood, Sh:

$$Sh = \frac{2r\varepsilon k_g}{D} \qquad (5)$$

This number usually is a function of the air velocity, but in laminar cases it becomes equal to 2 [4]. This is assumed to be the case. The bulk porosity of the carbon particles follows from the carbon load, L, and the density of the carbon particles, ρ_k, by assuming that one minus the porosity is occupied by the carbon:

$$(1-\varepsilon) = \frac{L}{2r\rho_k} \qquad (6)$$

Which gives:

$$C_{ini} \approx C_0 \exp\left(\frac{vr}{D}\left(1-\sqrt{1+\frac{6}{\left(\frac{r\rho_k}{L}-1\right)}\left(\frac{D}{rv}\right)^2}\right)\right) \tag{7}$$

This equation describes the initial breakthrough concentration of a vapour through a NBC-protective fabric with a carbon bead filter as a function of the air velocity through the material.

50 % breakthrough

The sigmoid breakthrough curve of the effluent vapour against time can be approximated by a block shaped curve, which changes at the time where 50% breakthrough occurs. Thus, the amount of vapour, which is adsorbed on the carbon, is equal to the dose at which the carbon material was exposed, $C_0 t_{50}$, times the velocity of the vapour through the material. Taking into account the carbon load gives equation:

$$q = \frac{C_0 t_{50} v \rho_k}{L} \tag{8}$$

q	adsorption capacity of carbon for vapour with concentration C_0 (kg/m^3)
C_0	challenge concentration of vapour (kg/m^3)
t_{50}	50% breakthrough time (s)
v	superficial velocity of the air through the clothing (m/s)
ρ_k	density of the carbon spheres (kg/m^3)
L	carbon load (kg/m^2)

or

$$t_{50} = \frac{Lq}{C_0 v \rho_k} \tag{9}$$

The adsorption isotherm is known as a function of the concentration, thus q is known. A Dubinin-Radushkevich isotherm is assumed [1-3]:

$$q = q_{\max} \exp\left(\left(\frac{RT}{\beta E_0}\right)^2 \ln^2\left(\frac{C}{C_{sat}}\right)\right) \tag{10}$$

q_{max}	maximum adsorption capacity of carbon for vapour (kg/m^3)
R	gas constant (J/mol K)
T	temperature (K)
β	affinity coefficient (-)
E_0	activation energy (J/mol)
C_{sat}	saturation concentration of vapour (kg/m^3)

Air permeability

The air permeability of the fabric together with the wind speed determines the air velocity through the clothing material. For the calculation of the flow rate the following empirical equation was used (5-6):

$$v = 0.559 \Gamma v_{wind}^2 \tag{11}$$

v	superficial velocity of the air through the clothing (m/s)
Γ	air permeability of clothing material (m/Pa s)
v_{wind}	air velocity of the wind (m/s)

Experimental

The experimental study was concerned with the evaluation of a broad range of air permeable carbon-based NBC-protective fabrics. The charcoal adsorbent was present in different forms: discrete carbon beads onto a textile fabric, carbon fibres and carbon powder incorporated into a nonwoven material or foam. The fabrics were evaluated on the following properties: air permeability, mustard vapour penetration and dynamic adsorption capacity for mustard vapour.

The air resistance of the fabrics was determined by measuring the pressure difference over a material sample, while blowing air through the material with a linear velocity of 1 or 5 cm/s. The air permeability was calculated as the reciprocal value of the air resistance.

The protective performance of the fabric samples was determined using a mustard vapour challenge test. A nitrogen stream with mustard vapour was drawn through the material samples. The concentration profile of the penetrated agent was measured using a gas chromatograph with a flame ionisation detector as a detection system and the penetrated dose was calculated. The flow rate through the material simulates the flow rate under actual field situation at a wind speed of 5 m/s and is the result of the wind speed and the air permeability of the material (equation 11). The vapour challenge concentration was 11 mg/m^3. The influence of the gas velocity through the material on the penetration of mustard vapour was determined for a carbon bead type fabric. The breakthrough of mustard was measured for gas velocities in the range of 0 – 8 cm/s.

The dynamic adsorption capacity of the materials was determined using a constant flow rate of 2 cm/s through the materials. The challenge concentration of mustard vapour was 230 mg/m^3. From the breakthrough curve the dynamic adsorption capacity of the materials was calculated as the difference between the challenge amount of mustard and the penetrated amount of mustard.

Results and discussion

Typical results of the fabric properties are presented in Figure 1. The protection levels afforded by the fabrics are given as penetrated dosage of mustard vapour after 6-hours challenge. From these results it appears that the air permeability is an important parameter on the breakthrough of mustard vapour. Generally, fabrics with a high air permeability offer a low protection. This is also the case if their dynamic adsorption capacity is relatively high. This is because an increase of the air permeability results in an increase of the air velocity through the fabric resulting both in a less effective mass transfer process of the vapour to the carbon and an increase of the mustard vapour challenge stream through the fabric. Figure 2 shows the penetrated dose of mustard vapour as a function of the quotient of air permeability and dynamic adsorption capacity of the fabrics. Because it can be expected that the mass transfer process of the vapour to the carbon depends on the type of the carbonaceous material, the fabrics were combined in two groups, the carbon bead materials and the other materials. It appears that linear regression results in a good fit for both groups of fabrics.

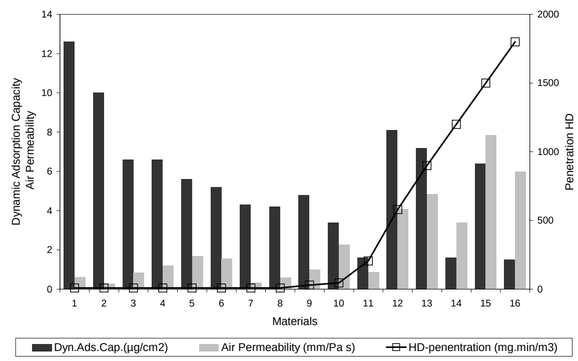

Figure 1: Fabric properties: dynamic adsorption capacity, air permeability, mustard vapour penetration.

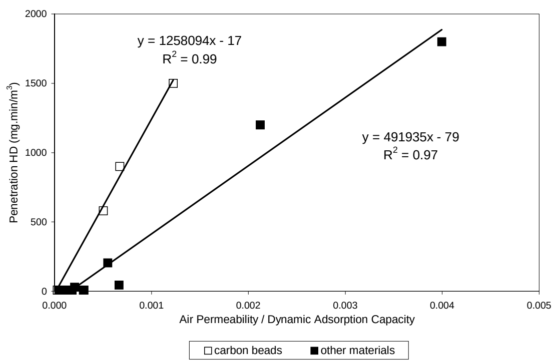

Figure 2: Correlation of the mustard vapour penetration with the ratio of air permeability and dynamic adsorption capacity.

Using the model, the influence of wind velocity and air permeability on the initial breakthrough and on the 50% breakthrough were calculated for the carbon bead type fabric. In both cases, all other important parameter values were kept constant. This values are shown in Table 1.

Table 1 Values of parameters, used in the model study.

C_0 =	11	mg/m^3	Γ =	0.002	m/(Pa s)
C_{sat} =	910	mg/m^3	v_{wind}	5	m/s
D =	$5.70*10^{-6}$	m^2/s	T =	298	K
q_{max} =	609	kg/m^3	r =	$2.50*10^{-4}$	m
E_0 =	$2.48*10^4$	J/mol	L =	0.177	kg/m^2
β =	1.55	-	ρ_k =	$1.01*10^3$	kg/m^3
R =	8.31	J/molK			

If the wind velocity and the air permeability of the clothing changes, Figure 3 and Figure 4 are found. The air velocity through the clothing depends on both the air permeability of the clothing and on the velocity of the wind. In Figure 5 the actual effect of changing the air velocity through the clothing on the initial breakthrough is shown. The curve in this figure represents the results of the model and the points are the experimental values. The time at which 50% breakthrough occurs is also dependent on the air velocity through the clothing. This effect is shown in Figure 6. The predictions of the model are in good agreement with the experimental results.

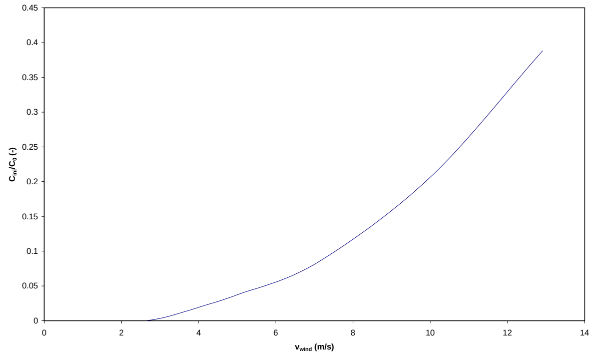

Figure 3: The effect of the velocity of the wind on the initial breakthrough.

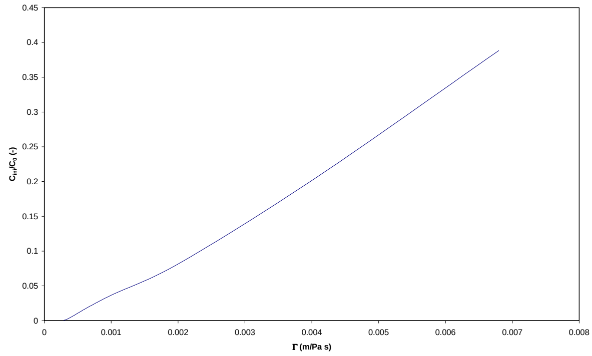

Figure 4: The effect of the air permeability of the clothing on the initial breakthrough.

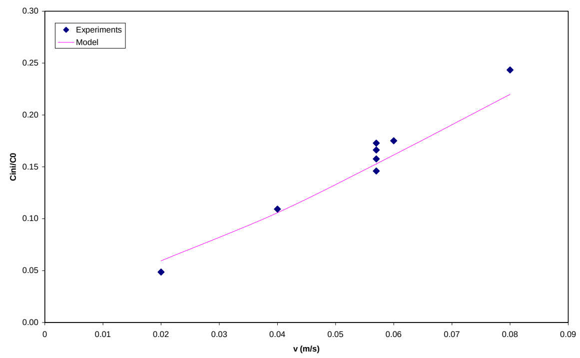

Figure 5: The effect of the air velocity through the clothing on the initial breakthrough (the curve represents the model, the points are experimental data).

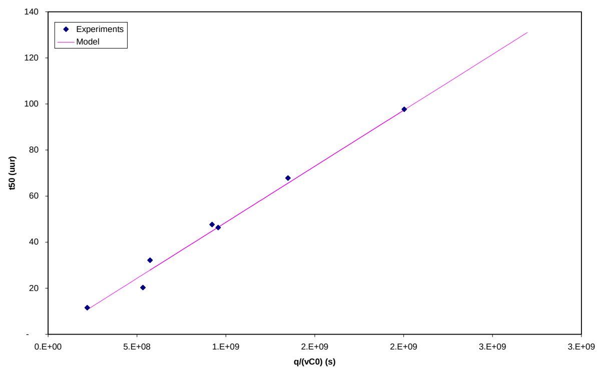

Figure 6: The effect of the air velocity through the clothing on the 50% breakthrough time (the curve represents the model, the points are experimental data).

The air velocity through the clothing results in an almost linear change in the initial breakthrough. The initial breakthrough is also almost linearly dependent on the air permeability of the clothing, which was to be expected because the air velocity through the clothing is linearly dependent on the permeability of the clothing. The wind speed have a parabolic effect on the initial breakthrough. All these effects seem quite obvious. A higher air velocity will result in less contact time between the air and the carbon, and therefore will result in a higher initial breakthrough concentration.
The 50% breakthrough time is inversely proportional to the velocity of the air through the clothing. If the air velocity is higher, more air will flow through the clothing during a certain time period. Thus more vapour must be adsorbed onto the carbon. This means that the carbon will reach its maximum adsorption capacity earlier, resulting in a decrease of the 50% breakthrough time.

Conclusions
Experimentally and theoretically, the effect of air permeability and wind speed on the chemical protective performance of NBC-protective fabrics has been studied. Higher air permeability and wind speed will result in a reduction of the protective performance of the fabrics. Therefore, the potentialities for reducing the heat load by means of improving the air permeability are limited. The proposed model for estimating the protective performance under various conditions can be used as a tool to seek for a good compromise between comfort and adequate protection.

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Application of a Computer Model to Set Heat Strain Threshold Limit Values: Evaluation During a Simulated Army Basic Combat Fitness Test

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Summary

The risk of exertional heat illness during military activities can be reduced by setting Threshold Limit Values (TLVs) using Wet Bulb Globe Temperature (WBGT) index. A study was undertaken to investigate if computer predictions of heat strain were accurate enough to set TLVs for military activities. Physiological strain during a simulated Army Basic Combat Fitness Test (treadmill walking at 6.8 km h^{-1}, 0% incline) in a warm environment (WBGT 24.3°C) was assessed in 20 apparently healthy male soldiers with no history of heat illness. Measured environmental variables, metabolic heat production, subject anthropometry, and estimated clothing thermal and evaporative resistances, were entered into a rational heat strain model. The range in measured rectal temperature (T_{re}) at the end of exercise was 37.7 to 39.3°C. T_{re} was correlated with exercise oxygen uptake (r = 0.68, P<0.001). Differences between predicted and measured T_{re} after 60 minutes and at the end of the simulated Army Basic Combat Fitness Test, or point of subject withdrawal, were +0.18 (1 SD = 0.37) and +0.03 (0.48)°C respectively. It was concluded that computer predictions of heat strain have potential value for setting valid TLVs for military activities.

Introduction

Exertional heat illness (EHI) is an important issue for the Armed Forces of many nations (*eg* Minard, 1961; Epstein *et al*, 1999). UK Forces have about 100 hospital admissions each year, mainly occurring as a result of forced marching or other field exercise (Bricknell, 1996). The risk of EHI can be reduced by setting Threshold Limit Values (TLVs) using a heat stress index such as the Wet Bulb Globe Temperature (WBGT). TLVs must reflect the interaction of many factors such as physical fitness and other individual characteristics, clothing and metabolic heat production. However, as a consequence of the multitude of factors that cause heat illness, realistic guidelines do not prevent all heat casualties. Table 1 displays, in modified form, the current TLVs for the UK Armed Forces (Ministry of Defence, 2001).

TLVs are often based solely on experience of the human consequences of heat stress. This pragmatic approach carries an unquantified risk to exposed personnel. An empirical approach, based on human experimental data, would give low-risk, validated TLVs, but at a high resource cost. A more versatile method would be to use computer-based models of thermoregulation to predict heat strain and hence to set TLVs with reduced risk.

Although it is impossible for models to incorporate all variables involved in thermoregulation, they are reliable in describing heat exchange and useful to predict thermal strain particularly when metabolic activity remains constant over the time of the given heat exposure (Gonzalez *et al*, 1997). Such conditions arise in the British Army Basic Combat Fitness Test (BCFT) that each soldier must pass annually. The BCFT, which has been associated with cases of EHI, requires personnel to complete a 12.8 km loaded march (at least 4.8 km off tarmac) in a time of 2 hours, but not less than 1 hour 55 minutes. The purpose of this study was to compare the measured and predicted heat strain induced by a simulated BCFT to assess if it is feasible to set TLVs using computer-based models.

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

Table 1: UK Armed Forces Heat Stress Threshold Limit Values

Threshold Limit Values (°C WBGT)		
Not heat acclimatised	**Heat acclimatised**	**Maximum work rate**
32°C	**No limit**	**Low** *eg* Lying, guard duty, driving
26°C	**30°C**	**Medium** *eg* Marching 3.6 km h^{-1} 30 kg load
24°C	**27°C**	**High** *eg* Marching 5.6 km h^{-1} 20 kg load
20°C	**25°C**	**Very high** *eg* Marching 8 km h^{-1} no load, marching 5.6 km h^{-1} 30 kg load (equates to the Army Basic Combat Fitness Test)
30 minutes at 20°C	**20°C**	**Extreme** *eg* running in sports kit

These values are expressed for a 1-hour exposure with a minimum of 30 minutes rest after the activity. They apply to men and women of equal fitness, wearing a single-layer uniform with sleeves rolled up and without helmets. An individual is considered to be heat acclimatised if they have undertaken regular exercise for longer than ten days in the same environmental conditions as the proposed activity.

Methods

Subjects

Twenty, apparently healthy, male soldiers volunteered to participate in the study. Subjects were not heat acclimatised and had no history of EHI. Selected physical characteristics of the subjects are given in Table 2.

Table 2: Subject physical characteristics

	Age (years)	**Height** (cm)	**Weight** (kg)	**Body fat** (%)	**VO_2 max** (ml kg^{-1} min^{-1})
Range	23-37	167-185	66.1-90.8	10.4-24.3	43.9-61.8
Mean (1SD)	30 (5.0)	176 (5.0)	80.7 (6.4)	17.4 (3.8)	53.8 (5.5)

Preliminary testing

Percentage body fat was estimated by skin-fold thickness at the biceps, triceps, subscapular and suprailiac sites (Durnin and Womersley, 1974). Aerobic fitness, expressed as maximum rate of oxygen uptake (VO_2 max), was measured during an incremental treadmill running test to volitional exhaustion.

Simulated Army Basic Combat Fitness Test

Activity: 120 minutes treadmill walking (incline 0%, speed 6.8 km h^{-1}) with 2-minute rest periods at 28, 58 and 88 minutes and 1-minute rest at 119 minutes. A 20.0 (1 SD = 0.3) kg backpack was carried. The mean oxygen uptake measured at 10 minutes was 2.0 (0.2) l min^{-1}. *Clothing:* The subjects wore cotton underpants and vest, lightweight combat trousers, woollen socks and leather boots. The clothing weight was 3.0 (0.3) kg; intrinsic thermal insulation (I_{cl}), 0.63 clo; Woodcock moisture permeability index (i_m), 0.55. *Environment:* Dry bulb temperature, 32°C; wet-bulb temperature, 21°C; relative humidity, 40%; water vapour pressure, 1.75 kPa; air speed, 2 m s^{-1}; WBGT, 24.3°C.

Subjects were encouraged to drink 6 ml kg^{-1} body weight of water every 30 minutes during the simulated BCFT. Subjects were withdrawn if: rectal temperature (T_{re}) reached 39.3°C; heart rate attained 95% of the measured maximum for 3 minutes; they withdrew themselves; or 120 minutes had elapsed.

Physiological Measurements

T_{re}, mean skin temperature (T_{sk}; Ramanathan, 1964) and heart rate were recorded every minute and averaged over 5-minute periods. Sweat rate (kg h^{-1}) was estimated from changes in nude body weight before and after the simulated BCFT, corrected for water consumed and urine produced. Expired air samples were obtained at 10 minutes to determine rate of oxygen uptake and rate of metabolic heat production (Weir, 1949).

Heat strain modelling

Measured environmental variables, metabolic heat production and subject anthropometry (height, body weight and % body fat), and estimated clothing thermal resistance and i_m, were entered into a rational heat strain model based on the Stolwijk and Hardy (1977) 25-node model of human thermoregulation. T_{re} was predicted for each subject at 1-minute intervals and compared with measured T_{re} at 60 minutes and at the end of exercise.

Statistical analysis

Linear regression analysis was undertaken on selected physiological variables. The alpha level was set at $P = 0.05$. Data are reported as mean values with 1 standard deviation (SD).

Results

12 subjects completed the simulated BCFT. 8 were withdrawn at times between 45 and 108 minutes: 4 with a T_{re} greater than 39.3°C; 1 with a heart rate greater than 95% of measured maximum; and there were 3 self-withdrawals due to headache and blisters. The range in measured T_{re} at the end of exercise was 37.7 to 39.3°C. At the end of exercise (or point of subject withdrawal), T_{sk} was 35.7 (0.9)°C; heart rate was 157 (19) beats min^{-1}; sweat rate was 1.3 (0.2) kg h^{-1}. T_{re} was not correlated with sweat rate, surface area:mass ratio, body weight or percentage body fat, but there was a linear correlation with exercise oxygen uptake ($P<0.001$; $r = 0.68$) and maximum rate of oxygen uptake ($P<0.02$; $r = 0.54$). The relationship between T_{re} and exercise oxygen uptake is shown in Figure 1.

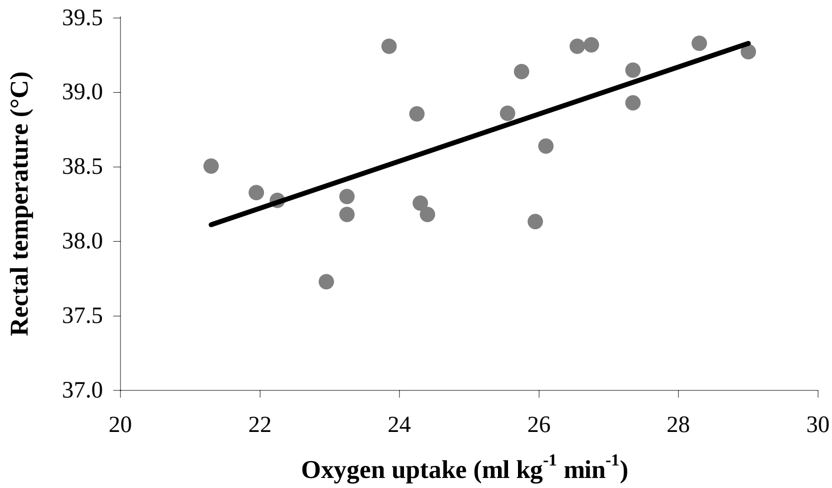

Figure 1: Correlation of rectal temperature with oxygen uptake for each of the 20 subjects

Measured and predicted T_{re} are displayed in Figure 2. The differences between predicted and measured T_{re} after 60 minutes and at the end of the simulated BCFT, or point of subject withdrawal, were +0.18 (0.37) and +0.03 (0.48)°C respectively.

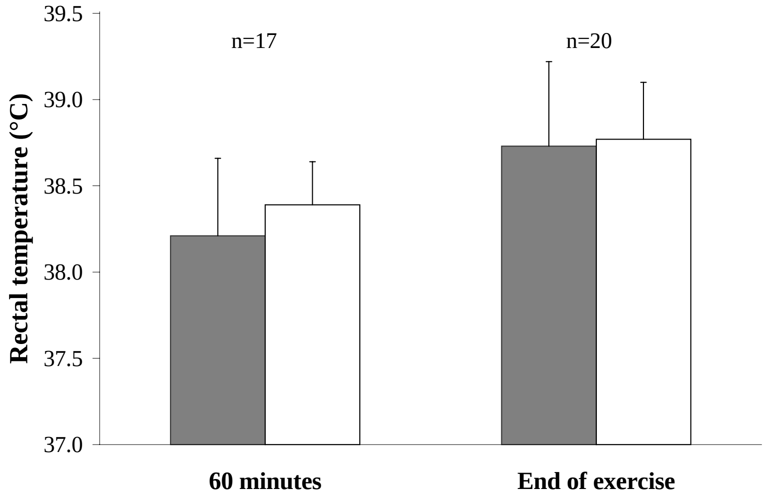

Figure 2: Measured (

at the end of the exercise period for each subject (1SD).

Data at 60 minutes are for 17 subjects; data at the end of exercise are for 20 subjects.

Two subjects (A and B) had a rate of rise of T_{re} ($T_{re\ rate}$) at 45 minutes more than 2 SD outside the mean of the other 18 subjects and were deemed to be heat intolerant. $T_{re\ rate}$ was 2.6 °C h^{-1} in subject A, 2.1°C h^{-1} in subject B and 1.3 (0.4) °C h^{-1} in the remaining 18 subjects (Figure 3).

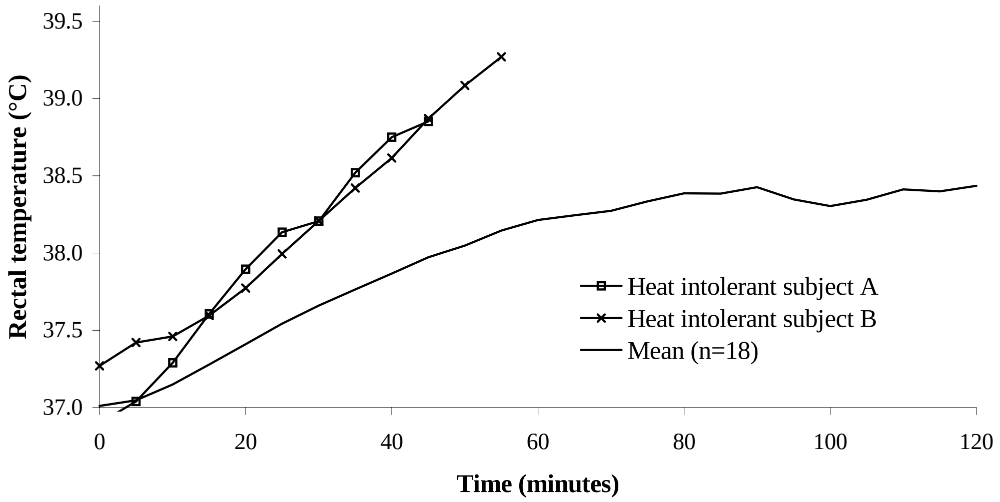

Figure 3: Rectal temperature during the simulated Basic Combat Fitness Test.
Data to 45 minutes are for 18 subjects. Thereafter subjects began
to withdraw. 12 subjects completed 120 minutes.

Discussion

There were large inter-subject differences in measured heat strain, which is typical of a cohort of otherwise healthy individuals. This variability was attributed, in part, to differences in metabolic efficiency during load carriage, as oxygen uptake during load carriage was correlated with T_{re}.

Two subjects appeared to be heat intolerant. These findings may relate to low aerobic fitness and high metabolic heat production in subject A, and impaired sweat loss in subject B. Subject B also had a high surface area:mass ratio, which has been correlated with heat strain (Havenith, 1995). Discussion of these

subjects is beyond the scope of this paper. Computer models cannot simulate the thermoregulatory responses of individuals, so such ‘outliers’ must be accounted for in TLVs by using wide confidence intervals.

Predicted mean T_{re} for the cohort was similar in magnitude and variance to measured T_{re}. Although it is impossible for computer-based models to incorporate all the variables involved in thermoregulation, these predictions show the degree of accuracy that can be achieved. We consider this sufficient accuracy to show that computer-based models have potential value for setting TLVs for other military activities.

Acknowledgements

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Microclimate Investigations on Permeable NBC Protective Garments

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1. Introduction

According to the **operational requirements of NATO**, NBC Protective Clothing Systems must be suitable for extended periods of wear in all climatic environments without creating unacceptable heat stress and serious reduction of the protective capability.

The demand for balancing wear comfort and protection confronts the developers with a challenging task. The physiological wearing properties of NBC Protective Garments can be improved for example, by reducing the activated carbon loaded filter layer in weight and thickness, or by increasing the air permeability. In most cases however, this results in the loss of protective capacity. By employing filter layers using activated carbon with hydrophilic properties, this disadvantage is avoided.

The properties of fabrics and ensembles which are most relevant to the physiological effects on the wearer are water-vapour and thermal resistance.

In addition, the **microclimate** plays an important role. It is influenced by the above-mentioned parameters and the trapped air between the clothing layers and underneath the clothing, which is determined by the flexibility of the fabrics as well as cut, pattern and fit of the garments.

The microclimate is particularly influenced by the ability of the textile layers for short-time water-vapour uptake and their moisture-buffering capacities: a good uptake and buffering of interstationary sweat pulses in the area close to the skin has the following effects:

- low increase in humidity immediately after the occurrence of the sweat pulses,
- small peak value of humidity, and
- fast decrease of humidity in the microclimate.

Since temperature also decreases together with humidity, the positive effects on the subjective wearing comfort are considerable.

2. Methods and results

Please refer to the following 4 figures.

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

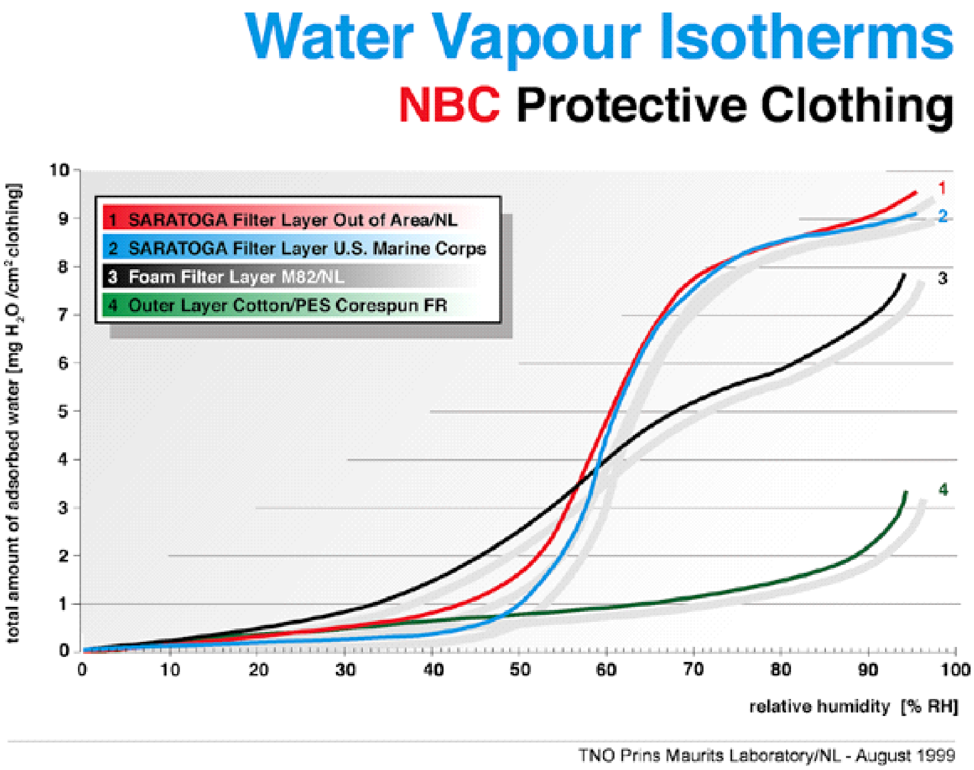

Figure 1: Calorimetric Test Method - Thermochimica Acta No. 34 (1979 page 109)

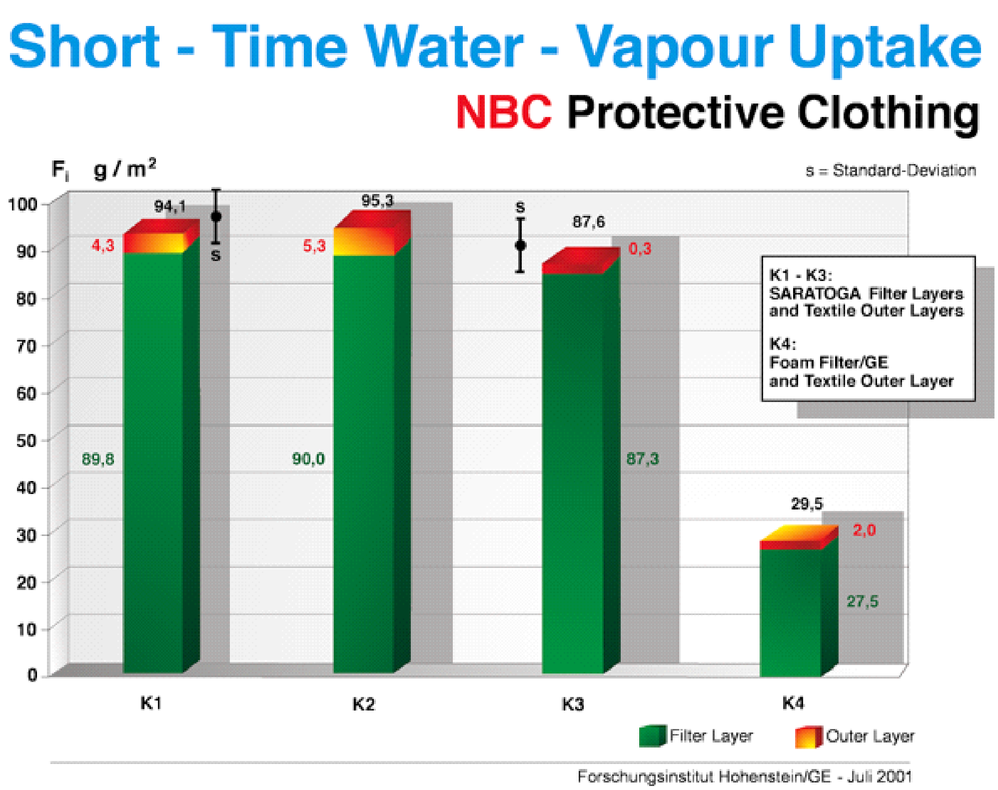

Figure 2: Skin Model Measurement - DIN EN 31092 (02/94) / ISO 11092 (10/93)

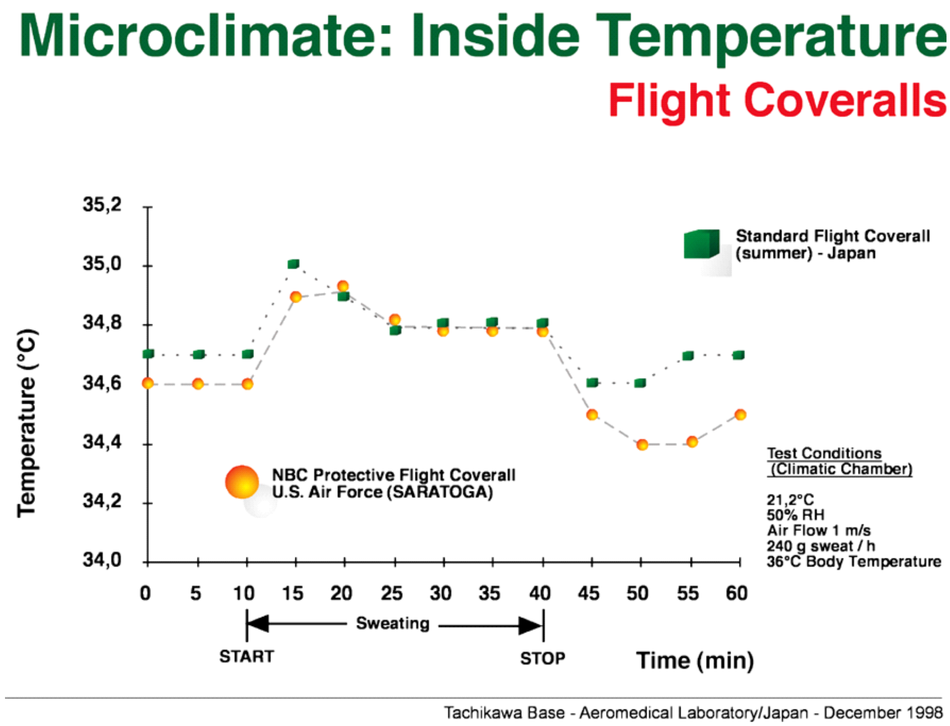

Figure 3: Climatic Chamber Test using TOM-III sweating mannequin of TOYOBO

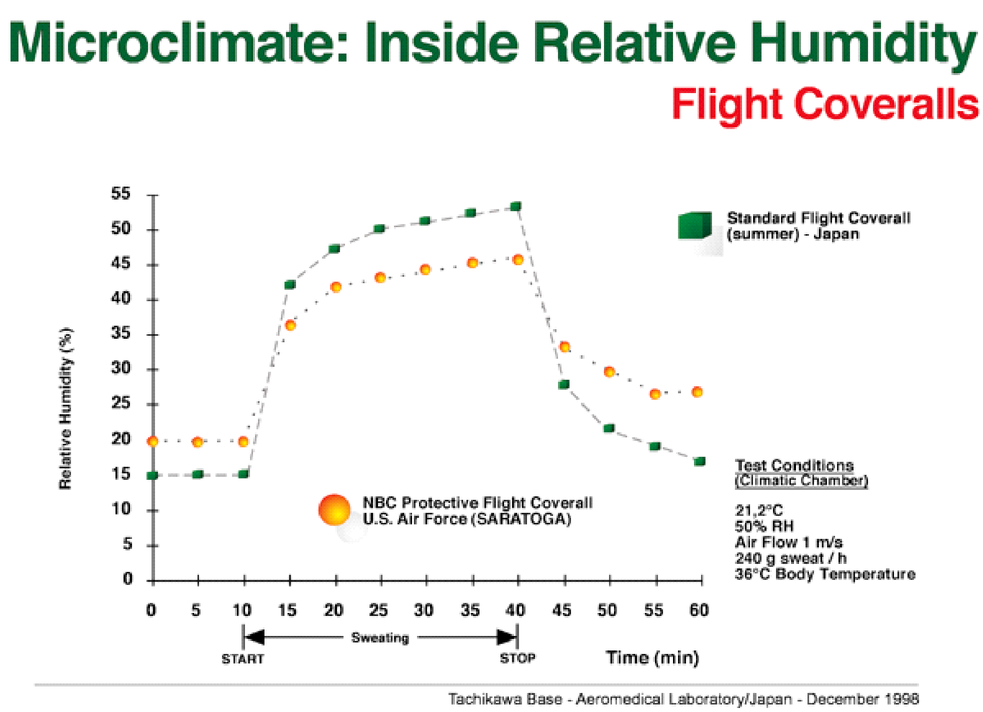

Figure 4: Climatic Chamber Test using TOM-III sweating mannequin of TOYOBO

3. Discussion

The ability for **short-time water-vapour uptake** of filter layers on the basis of activated carbon in the form of spherical adsorbents (SARATOGA™), compared to foam filter layers is very high. The main reason for this are the **hydrophilic properties** of the spherical adsorbents. Another reason is the **free accessibility of the adsorbents** for water-vapour molecules. Whereas the particles of the activated carbon powder used in foam filter layers are covered by a layer of adhesive, the outer surface and thus also the pore system of the spherical adsorbents are accessible without hindrance.

The **water-vapour buffering capacity** of filter layers on the basis of spherical adsorbents is also very high. The moisture regulation index of 0,40 to 0,42, established by the Forschungsinstitut Hohenstein / Germany (Interstationary Skin Model Measurement - Hohenstein Standard Test Specification BPI 1.2.) corresponds to that of working clothes and can be described as being good regarding its wear comfort.

As the water-vapour molecules in the spherical adsorbents are bound only very lightly, the moisture is easily desorbed and transported to the outside due to the existing pressure gradient.

The results of climatic chamber tests conducted in Japan using a "sweating mannequin", very clearly demonstrate the influence of filter layers with spherical adsorbents on a pleasant microclimate.
The established values for **inside relative humidity and inside temperature** are better for the SARATOGA™ Flight Coverall of the U.S. Air Force than for the light and fluffy summer Flight Coverall of the Japanese Air Self-Defence Force, which does not have an activated carbon layer.

Moisture in the spherical adsorbents has no remarkable influence on the protective capacity. Molecules of skin damaging and skin penetrating chemical warfare agents, due to their considerable higher heat of adsorption, very quickly displace the water-vapour molecules.

4. Conclusion

NBC Protective Garments on the basis of the spherical adsorbents technology (SARATOGA™) offer the best possible wearing comfort, in particular under hot and humid climatic conditions, without impairing chemical protection.
This has been proven practically in several field trials conducted over the past few years (U.S. Marine Corps, Joint Service Lightweight Integrated Suit Technology Program of the U.S. Forces, German Army and Air Force, Hungarian and Dutch Army).

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Stress (physiology)
Sweating
Temperature regulation
Thermal instrumented manikins
Thermal insulation
Thermal protective clothing
Thermal stress
Thermoregulation

14. Abstract

Exposure to heat and cold, as well as the thermal stress induced by protective clothing strongly influences operational effectivity of the soldier. On 8-10 October 2001, NATO and Partner for Peace nationals met in Dresden, Germany, to discuss the interaction between the climate, the clothing and equipment, and the physiology of the soldier in relation to its impact on the soldier's health and operational performance. 118 people participated in the meeting, originating from 20 countries, attending a total of 43 papers. Session topics were: 'Advances in clothing technology', 'advanced technology for heat stress mitigation', 'military benefits of physiological adaptation to heat and cold', and 'modelling, monitoring and thermal limits'. Apart from the military aspects, also the spin-off of the research for civilians and emergency services was discussed and this was seen as an important application of the research findings. Other observed themes were: -The sharply increased use of manikins in clothing and threat (steam, fire) evaluation; -The successful development of personal cooling systems and the development of good evaluation methods; -The use of spacer materials in heat protection, as well as for creating spacers in clothing through which air for active cooling can be provided; -The continued development of NBC protective clothing towards minimal heat stress; -The optimisation of heat and cold adaptation of soldiers before going on missions to respective areas; -The increase in successful use of models for prediction of heat and cold stress, survival time (hypothermia), frost bite risk, water requirements, clothing thermal performance, and for hypothesis testing in terms of the thermoregulatory system; -The development of new indices; for classification of physiological strain (heat and cold) and for the climate.

In the discussions topics for future joint projects or meeting were defined: -Thermoregulatory fatigue; -An inter-laboratory comparison of performance of dry and sweating thermal manikins; -The creation of a (black-box) electronic climate analyser which would use sophisticated heat balance analyses or even physiological models to transform the climatic measurements of the device into a simple heat stress index for use in the field which eventually could replace WBGT instead of mimic it.

The symposium provided an excellent overview of recent research and developments in the area and provided substantial food for thought and ideas for future work.

Given the speed of development in this area, a follow up symposium on the same topic would be valuable in three to five years. Special topic meetings as suggested above, would be relevant before that date.

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